Environmental Metrics for WEEE Collection and Recycling Programs

Dissertation
zur Erlangung des Doktorgrades (Dr. rer. nat.)
der Mathematisch-Naturwissenschaftlichen Fakultät
der Universität Augsburg

vorgelegt von
Irina Oswald

Institut für Materials Ressource Management (MRM)
Lehrstuhl für Ressourcenstrategie

Augsburg, Januar 2013

1. Gutachter	Prof. Dr. Armin Reller
2. Gutachter	Prof. Dr. Stefanie Hellweg

Tag der mündlichen Prüfung: 14. März 2013

Abstract

The take back and recycling of waste electrical and electronic equipment (WEEE) is of major importance for electronics producers due to mandatory take back regulations, as well as a commitment to producer responsibility and resource conservation. WEEE collection programs require metrics to measure performance and progress over time. Current metrics are not providing an impetus for the improvement of program quality and environmental effectiveness. This research proposes an alternative metric to measure the success of producers' collection and recycling programs, by focusing attention on raw materials recovery and the environmental benefits of recycling. Previous research is analyzed and used as a baseline for the development of the 'Avoided Environmental Burden' (AEB) metric. Sensitivity analysis is performed to demonstrate possibilities for corporate performance improvement. The AEB metric captures different environmental dimensions, namely energy, exergy, greenhouse gas emissions, ecological footprint, acidification, eutrophication and human toxicity potential. To test the robustness of the approach, the metric is validated against the results of an empirical WEEE sampling and pre-processing trial. In this trial, the yields of six materials are assessed and inefficiencies in material separation and recovery are identified. The AEB performance of the trial is compared with the results of two modeled recycling scenarios. The results of the analysis show that collection and recycling program performance can be improved by at least 40% if raw materials are recovered at a higher rate in pre-processing. As for the modeled cases, the research demonstrates that the collection of environmentally impactful material is useful to maximize program performance, but the potential is only fully tapped if producers select the most efficient recycling process for the treatment of the collected WEEE. The results of the analysis demonstrate that the AEB metric is a powerful tool for companies to estimate the environmental performance of collection programs at the planning stage, which in turn enables strategic program development. The AEB metric is more effective than mass and unit based metrics as it motivates producers to actively engage with the downstream recycling chain and make informed decisions based on eco-efficiency considerations.

Acknowledgement

I would like to thank my supervisor Prof. Armin Reller for his support and guidance. His knowledge and enthusiasm to research society's use of natural resources were a key source of inspiration for me.

I would also like to thank Prof. Stefanie Hellweg for accepting to become co-supervisor of my thesis and for giving so generously of her time and expertise. I am very grateful for her productive suggestions to improve my research.

I would like to thank my thesis committee, especially Prof. Axel Tuma for his interest in my work and helpful feedback.

Special thanks must go to Julian Maruschke, Jeff Dahmus and Simon Meissner. I am so grateful for their willingness to discuss my research and read through draft chapters. Their critical questions and constructive feedback have substantially improved this research.

I would like to thank my colleagues and fellow PhD candidates at Lehrstuhl für Ressourcenstrategie for their collaboration and friendship.

I owe many thanks to my family and friends, especially my parents for their continued support, my brothers Korbinian and Severin for invaluable tech support, and Korbi for his constant encouragement, companionship and sense of humor.

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List of Abbreviations

a	year
AEB	Avoided Environmental Burden
AP	Acidification Potential
BOF	Basic Oxygen Furnace
BOM	Bill of Materials
CE	Consumer Electronics
CED	Cumulative Energy Demand
CExD	Cumulative Exergy Demand
CI	Confidence Interval
CPR	Collective Producer Responsibility
CRT	Cathode Ray Tube
CSR	Corporate Social Responsibility
e	equivalent
EAF	Electric Arc Furnace
EAR	Stiftung Elektro-Altgeräte Register
EEE	Electrical and Electronic Equipment
EF	Ecological Footprint
EHS	Environment Health and Safety
EOL	End of Life
EPR	Extended Producer Responsibility
EU	European Union
FPD	Flat Panel Display
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GLO	Global
GRI	Global Reporting Initiative
GWP	Global Warming Potential
HD	Hard Drive

HTP	Human Toxicity Potential
IC	Integrated Circuit
ICP-AES	Inductively Coupled Plasma Atomic Emission Spectrometry
ICT	Information and Communication Technology
IPR	Individual Producer Responsibility
IT	Information Technology
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MFA	Material Flow Analysis
NGO	Non Governmental Organization (NGO)
NP	Nutrification Potential
OEM	Original Equipment Manufacturer
PC	Personal Computer
PCB	Printed Circuit Board
PGM	Platinum Group Metals
PM	Precious Metal
POM	Put on Market
ppm	parts per million
PVC	Photovoltaic Cell
QWERTY	Quotes for Environmentally Weighted Recyclability
RER	European Countries
RoHS	Restriction of Hazardous Substances
SCEE	Sony Computer Entertainment Europe
SFA	Substance Flow Analysis
SWICO	Schweizerischer Wirtschaftsverband der Informations-, Kommunikations- und Organisationstechnik
TC	Transfer Coefficient
UN	United Nations
WEEE	Waste Electrical and Electronic Equipment

"The role of an indicator is to indicate, not to dictate:
This implies that the actual scores of an indicator are not the goal,
but only the means to our broader plan."
Theodore S. Benetatos [13]

Thesis Structure

The research documented in this thesis proposes a methodology for original equipment manufacturers (OEMs) to measure the performance of waste electrical and electronic equipment (WEEE) collection and recycling programs. The structure of the thesis reflects the research approach: description of the problem and research motivation (chapter 1), development (chapter 2) and validation (chapter 3 and chapter 4) of the methodology, and discussion of the results (chapter 5)(see Figure 0.1).

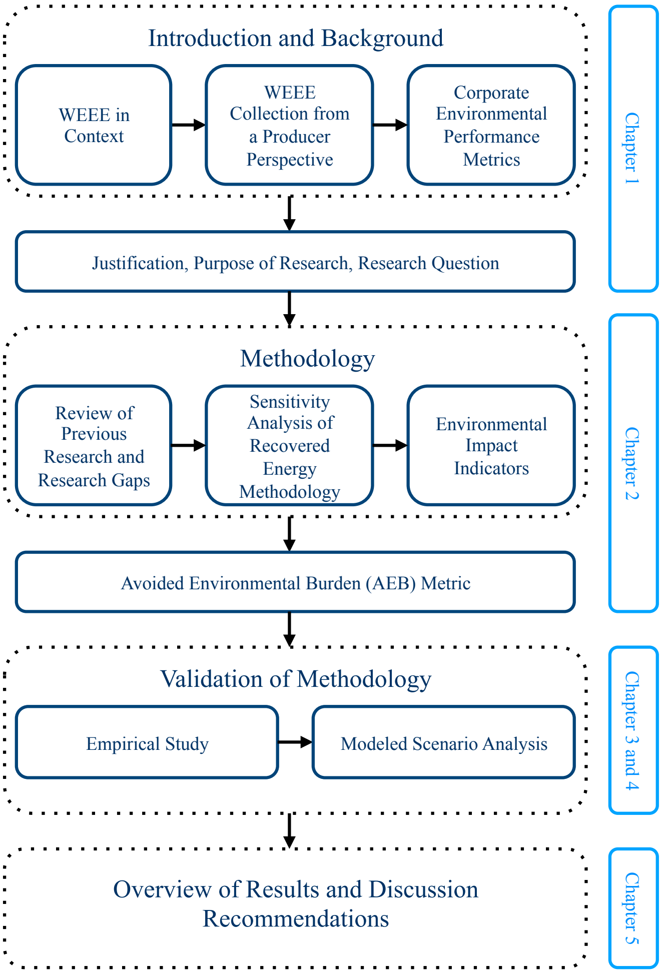


Figure 0.1: Overview of Thesis Structure

Chapter 1 outlines the environmental impact and resource implications of WEEE generation, and summarizes the concept of Extended Producer Responsibility (EPR). The work presented here looks at WEEE collection from an industry perspective. The main aim of this chapter is to demonstrate that the existing metrics do not motivate industry to

improve the quality of WEEE collection programs, are not informative with respect to environmental impact and are not helpful in guiding the WEEE collection strategy of a company.
In chapter 2 an overview is given on previous research investigating corporate performance and process performance metrics in the context of WEEE recycling. Critical research gaps are identified and the development of a novel metric is proposed. The methodology that underlies the metric is built on the 'recovered energy' approach and analyzed with respect to the sensitivity of its system variables. The analysis shows that there are multiple opportunities for OEMs to improve collection programs and improve corporate performance in WEEE collection and recycling. A number of environmental impact indicators are combined with the methodology. The scope of these indicators is outlined and input data are discussed in detail.
Chapter 3 demonstrates a baseline case of information and communication technology (ICT) waste collection and recycling. Sampling analysis and a pre-processing trial are carried out empirically and described in this part of the thesis. The aim of the trial is to build a reference scenario that illustrates the current situation of ICT waste recycling. The primary data obtained in the trial is used to validate the metric and show the environmental performance of a realistic case of raw materials recovery from ICT waste. The performance of the realistic case is compared against the performance of an ideal case, in which higher recycling rates are reached in pre-processing. The comparison of the actual performance (realistic case) and the potential performance (ideal case) demonstrates the impact of recycling process recovery rates on the producer's corporate performance.
In chapter 4 two scenario cases are modeled. The aim of this chapter is to understand the value of a program tailored to one specific type of waste, and to compare and discuss the performance of the empirical case with the performance of two modeled cases (scenarios). In both scenarios it is assumed that only end of life (EOL) mobile phones are collected. The main difference between the two cases is that different recycling processes for treatment of the collected phones are assumed. As in the empirical case, the proposed methodology is applied to the results of the modeled cases. The modeled cases demonstrate the impact of the type of WEEE collected and process performance on corporate performance.
Chapter 5 outlines the strengths and weaknesses of the methodology and discusses the role of OEMs in the WEEE collection and recycling system. The thesis concludes with recommendations for OEMs, operators of recycling facilities and policy makers, and discusses opportunities for further research.

WEEE is a very diverse waste category, which is why the research scope must be limited to one product group. The focus of this research is on ICT equipment and producers of this type of electronics. However, the methodology is applicable to any other type of WEEE and producers of other types of electronics.

1 Background

The following chapter outlines background information, which sets the motivation for this research in context. The issue of WEEE has been investigated by many different disciplines, from the viewpoint of engineers, natural scientists, economists, lawyers and social scientists. This is not to give a comprehensive overview on the numerous problems around WEEE and the work that has been undertaken in this field, but to point out aspects that are important to understand the relevance of this research. All background information presented here serves as a reference for the research motivation.

1.1 Electronic Waste in Context

The term WEEE refers to any appliance using electrical power supply, which has reached the end of its useful life. The consumer disposes of a product either because it is no longer operational or because it is replaced by more advanced technology and design (i.e. the product becomes obsolete).

The first publications on the environmental implications of WEEE appeared in the late 1990 s [101, 115, 118, 157, 163], after a decade in which the use of personal computing and mobile telecommunications had become standard in both home and business environments in many high-income countries[1]. For the past 30 years there has been a progressive increase in WEEE generation worldwide. The United Nations (UN) refer to WEEE as the fastest growing waste stream [178]. Recent estimates suggest that WEEE is expected to increase by 24% between the years 2008 and 2014 in the 27 member states of the European Union (EU 27), reaching about 10.4 million tonnes (t) in 2014 [79] and 12.3 million t in 2020 [80]. In Germany, the generation of waste information technology (IT) equipment is expected to increase by 72% between 2008 and 2013 [150].

Along with rapid technological development and strong consumer demand [37], a number of factors have enabled the waste stream to grow (and will likely continue to do so):

(1) The price of many electronics have gradually dropped over the past 20 years, making it more affordable for a wide variety of income groups to buy electronic products [14]. Research on the price development of IT hardware suggest that globalized production and a decline in semiconductor prices led to an average price decline of 20% between the years 1995 and 2002 [111]. Conservative estimations suggest a price decline of around 23% for modems and 15% for mobile phones between the years 1994 and 2000, while the prices for communications equipment on average fell between 5.5

[1] The definition of low, middle and high income countries adheres to the 2010 classification by the World Bank (low income: gross national income (GNI) per capita (p.c.) USD 1,005 or less; middle income: GNI p.c. USD 1,006 to USD 3,975 (lower), USD 3,976 to USD 12,275 (upper); high income: GNI p.c. USD 12,276 or more).

and 10.5% [48]. Overall, it can be assumed that decreasing prices led to increased consumption, more frequent replacement and a more rapid rate at which WEEE was (and is) generated.

(2) Many products which formerly did not contain electronic components or batteries, are now powered by electricity, for example a variety of household appliances and small electrical and electronic equipment (EEE) (e.g. photo frames, toothbrushes, greeting cards). Modern passenger cars routinely include car computers, displays, navigation and advanced hi-fi systems. As a consequence, WEEE is no longer generated exclusively from traditional EEE, but also from other consumer goods.

(3) Research suggests that there is a strong correlation between the gross domestic product (GDP) (as an indicator of economic performance) of a country and the amount of WEEE generated (measured as the amount of personal computers per 100 people) [146]. The study of [193] predicts that the amount of EOL personal computers (PCs) generated in developing (currently low- and middle income) countries will exceed that of developed countries by 2016 - 2018 (due to increasing economic development and welfare). According to this study, the year 2030 will mark the point at which more EOL PCs will be generated in developing countries (400 - 700 million units) than in developed countries (200 - 300 million units).

1.1.1 Environmental and Resource Concerns

WEEE is a complex waste category with respect to the large number of substances that are contained in EOL electronics. Some of these substances are toxic, e.g. lead and mercury, some are valuable, e.g. gold and palladium, and some are both, e.g. silver and cobalt.

The toxicity of WEEE has been in the focus of many studies investigating the international trade and illegal export of WEEE, and treatment of WEEE in low- and middle-income countries [7, 92, 142, 172, 191]. These studies document a variety of substandard recycling practices, for example open burning of monitors and chemical leaching of PCBs, which are common in e.g. Ghana and China and which cause the release of toxic substances into the environment [138, 191]. Many investigations find elevated concentrations of heavy metals and flame retardants in air, water and soil in the proximity of WEEE disposal and recycling sites. As a result of poor labor conditions, workers are directly exposed to toxic fumes and liquids. Residents in the area of WEEE recycling sites are exposed to contaminated drinking water and air [84]. Because the international trade in WEEE and unsafe treatment processes are difficult to control, legislation addresses the issue by restricting the use of certain chemicals in electronic products. In the EU, a directive known as the 'Directive on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment' (RoHS Directive) bans (with a few exceptions) the use of lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyl and diphenyl ether in

EEE put on market (POM) after 2006 [53].
While toxicity issues were discussed early on in the research around WEEE, a large number of recent publications refer to WEEE in the context of 'urban mining' and material value recovery [18, 25, 29, 155, 174, 186][2]. Precious metals, particularly gold and platinum group metals (PGM) are the most valuable substances in WEEE and their concentration is often higher in WEEE than in the original virgin ores. Ore grades for precious metals usually vary, but even in the highest grade ore, the concentration of gold is over 60% lower than in desktop PCs[3]. Precious metals (PM) are primarily found in printed circuit boards (PCB) and integrated circuits (IC), which are also the components with the most diverse mix of substances in WEEE [153]. Precious metals concentration varies by type of the board or chip. The most high-grade PCBs and ICs can be found in e.g. PCs, laptop computers, cell phones and modems. Lower grade PCBs and ICs can be found in e.g. cathode ray tube (CRT) monitors, printers and audio equipment.

With few exceptions, electronics are fabricated from non-renewable raw materials. Some of these materials are regarded as 'critical' [25]. There is no consistent definition of the term 'critical' in the existing literature, but a substance is typically characterized as critical if demand for it is expected to grow substantially in the future, availability is limited (e.g. geologically, technically and economically), and if there are constraint possibilities for substitution and/or recycling [35, 50, 65]. Production of many 'critical' materials is located in only a few countries at present, posing additional risks on import dependent economies [5, 174]. Determining the 'criticality' of a material is complicated by the impossibility to predict future technological developments and demand for certain raw materials [65]. 'Criticality' is also a contextual concept in that materials are usually characterized pertaining to a specific geography or industry. For example, a material may be essential for the energy sector, but irrelevant for the electronics industry. Notwithstanding these limitations, there is consensus among previous studies that a number of substances defined as 'critical' are of major importance for the ICT industry [5, 25, 26, 50, 129, 186]. Among these materials are:

Indium, which is used in the form of indium tin oxide in flat panel displays (FPD). Currently, an estimated 74% of global indium consumption is used for the production of FPD and demand from the ICT industry is expected to increase further. As part of the transformation of energy supply systems, demand is also expected to increase from the photovoltaic (PV) industry for the production of thin-film PV cells [1]. Indium is a by-product of zinc mining, so primary production of indium heavily depends on zinc production and demand [174]. Of the total production of indium, 52% was located in

[2] The term 'urban mining', i.e. the extraction of secondary raw materials from post-consumer waste reflects the notion that WEEE is able to supply raw materials for the application in new products.
[3] Lowest ore grade 105 kg ore/kg gold [93], concentration of gold 26 ppm/t of desktop PCs [59].

China in 2010 [1][4]. Indium is mainly produced from primary sources and the overall recycling rate of indium is $< 1\%$ [64]. Most of the recycled indium comes from recycling of post-industrial waste [186]. In the EU, recycling of FPDs currently does not include indium recovery [18][5]. Recovery of indium from FPDs is not cost-effective at present, as the concentration of Indium is low and the price at which the raw material currently sells on the market does not cover the investments necessary for recycling process development and implementation [41]. The main concern recycling operations have about FPDs are mercury containing backlights, i.e. concerns related to toxicity, rather than recovery of a critical material. Recycling technologies have been developed in Japan and Korea, but are not implemented globally and on a large scale [186]. Efforts to develop such processes will continue as indium demand and prices are expected to increase further in the future [18, 41, 186].

Tantalum, which is mainly used in capacitors in EEE. Tantalum is a very good conductor of heat and energy, and also extremely resistant to corrosion. These unique chemical properties of tantalum result in high capacitance per unit volume, which can be used in small EEE (e.g. cell phones, tablet computers). Of the total tantalum consumption, 60% is currently used for the production of capacitors [50]. Tantalum is mined from different types of minerals, for example columbite-tantalite (coltan). As of 2011, the majority of global tantalum production was located in Brazil, but it is also produced in a number of countries in Central Africa (e.g. Congo, Rwanda, Uganda) [133]. Tantalum has been referred to as a 'conflict mineral' as the conditions under which coltan is extracted in Congo reportedly involve illegal mining, forced labor and other unethical working conditions [12,139]. Similar to indium, the recycling rate of tantalum is estimated to be $< 1\%$ [64]. Tantalum is recycled from post-industrial waste, but there is currently no recycling from post-consumer waste, such as WEEE. The concentration of tantalum is low in WEEE and recovery from post-consumer waste is not cost effective to date. There are also technical challenges to recycle tantalum from WEEE. Tantalum containing capacitors are usually soldered onto PCBs, which are not disassembled prior to processing of the PCBs in a copper smelter. Tantalum is not recovered and transferred to slag in this smelting process [26].

Palladium, which has a number of applications in contacts, circuits, bonding wires, solders and multi-layer capacitors in EEE [25, 29, 50]. Unlike tantalum and indium, the main application of palladium is not in the electronics, but in the automobile industry. About 50% of global palladium consumption goes to the production of automotive catalysts, and only 19% is used in the production of electronics [26]. This is not to say that the

4 'Degree of production concentration' (often quantified with the Herfindahl-Hirschman index) is one of the indicators used in previous 'criticality' assessments [50, 65].

5 In this research, the terms 'recovery' and 'recycling' are not used in the strictest sense. Traditionally, 'recycling' implies that material is recovered as reusable material, while 'recovery' also covers waste to energy incineration. Because the scope of this research is clear, both terms are used to describe the extraction and processing of secondary raw materials from waste.

amounts of palladium in WEEE are insignificant, as is shown in the study of [29], which estimates that the small WEEE generated in Germany in 2007 (0.37 - 0.43 million t) contained approx. 700 kilograms (kg) of palladium. Palladium occurs and is mined coupled with other PGM (ruthenium, rhodium, osmium, iridium and platinum), predominantly in Russia (44%) and South Africa (37%) [109]. The large majority of production of palladium is thus concentrated in only two countries. The study of [26] estimates that market demand for palladium will increase by 63 - 99% between 2004 and 2025, due to increasing demand from the automotive and electronics industry. Palladium can be substituted with platinum in some electronic applications, but market prices of platinum are higher than palladium prices. Recycling technologies for palladium recovery from WEEE are available; for example, a copper smelting process is able to recover palladium from PCBs at a rate of 98% [77]. Palladium recycling from WEEE scrap is efficient at the metallurgical stage of the recycling chain, however previous research shows that the rate at which palladium is recovered at the pre-processing stage of WEEE recycling is $< 25\%$ [30]. In considering the different steps of WEEE recycling, recovery of palladium still needs to be improved.

The substances listed here aim at illustrating some of the parameters that determine 'criticality' and outline the concerns around availability, scarcity, recyclability and substitutability in concrete terms[6]. Needless to say, the list of critical materials in WEEE also includes other materials, for example gallium, neodymium and other rare earth elements, platinum and other PGM, and germanium [25]. The issue of production concentration is illustrated in the palladium and indium cases. For both substances, the ICT industry potentially also faces competition in terms of increasing demand from other industry sectors. The main risk associated with indium and tantalum is the lack of technologies available to recover these substances from WEEE in a profitable way. Currently, along with other critical substances, indium and tantalum become irreversibly diluted in many different material streams during WEEE recycling. As for palladium, the WEEE recycling chain still needs to be optimized to tap the full potential of palladium recycling from WEEE. The primary production of tantalum is an example of adverse social impacts resulting from virgin materials production. All three substances share a number of 'criticality' parameters, such as limited geological availability and unique chemical properties, which result in increased demand and limited possibilities for substitution. Many emerging technologies, such as ICT profoundly depend on the availability of materials that are considered as critical. Developing recycling technologies and strategies to access secondary sources of supply can help the industry to reduce their reliance on primary sources of supply.

Apart from technological challenges, further barriers for secondary raw materials recovery from WEEE are low collection rates, which complicate the challenge of effective WEEE

[6] For the issue of substitutability, the author refers to the study of [100], who analyze the performance of three different types of capacitors in terms of material functionality, economic implications and criticality of embedded substances.

management. Bulkier products (e.g. white goods: $>30\%$) usually show better rates than small products (e.g. monitors: $<30\%$), but the overall collection rate of WEEE is below 40% across all product categories in the EU [79][7]. While there is little data on the amounts of WEEE generated and potentially available for collection globally, a recent study in the Netherlands estimates that around 10% of the WEEE generated is exported as second-hand equipment, up to 25% is captured by non-official collection and the destination of some WEEE is unknown [82]. Collection of WEEE by informal parties and systems often involves illegal export of WEEE, which leads to adverse environmental impacts in the receiving countries and a loss of secondary raw material sources.

1.1.2 Producer Responsibility and WEEE Legislation

EPR is a regulatory instrument, which is based on the perception that the total product life cycle (including recycling and final disposal) must be considered in order to account for the environmental impact of a product. The aim of EPR is to decrease this environmental impact by placing the responsibility for take back, recycling and disposal on the producers. In making producers responsible for the EOL product management, the development of more environmentally friendly EEE is encouraged. According to the definition of [106], EPR includes economic, physical and informative responsibility. Economic responsibility describes the responsibility of producers to cover the costs of EOL product management, while physical responsibility includes the set up of collection infrastructure and logistics. Informative responsibility involves communication of relevant environmental information along with products sold.
One of the assumptions behind EPR is that disposal and recycling costs will influence the pricing of products, as manufacturers transfer increased life cycle costs to consumers [149]. While traditional pricing is based on the cost for raw materials and production (amongst others), EPR leads to the inclusion of EOL costs in product prices. It is assumed that manufacturers will aim to decrease the cost for EOL management by including disposal and recycling considerations into the design process of products (e.g. design for recycling, avoidance of hazardous substances) [15, 152]. EPR is thus considered to be an indirect measure to encourage the production of more environmentally friendly products.

WEEE Directive: In the EU, the management of WEEE is regulated through the 'Waste Electrical and Electronic Equipment Directive' (WEEE Directive), which was first enacted in 2003 and subject to a revision process from 2008 to 2012[8]. The recast of the Directive entered into force in August 2012. The European member states are expected to transpose the recast into national law by the year 2014. The WEEE Directive and its recast are based on the principle of EPR in stating that producers bear the costs for the collection,

[7] 2008 figures, as a comparison of estimated amounts of WEEE generated (based on amount of EEE put on the market three years prior) and WEEE collected.
[8] As this thesis was submitted the transposition of the recast was ongoing. Therefore, if not indicated otherwise, most of the information in this section refers to the original Directive.

treatment and disposal of WEEE from private households. Take back obligations are calculated from the individual producer's market share based on the total amount of products POM by all producers. This covers all products POM after 2005 (Article 8). The producers are collectively responsible for take back of historic waste, i.e. equipment POM prior to the year 2005. The assignment of all cost for WEEE recycling and disposal also means WEEE from private households can be returned to collection points free of charge across the EU 27 [52].

Metrics and Targets: The original Directive includes a collection target of an average of 4 kg of WEEE per person and year (Article 5), as well as some provisions for the treatment of WEEE (e.g. requirements for the removal of hazardous and valuable components, requirements for the treatment of CRT) (Annex II) and recovery targets for each product category (expressed as a % of product weight) (Article 7) [52]. The recast of the Directive introduces higher targets for the collection and treatment of WEEE to be brought into force four (seven respectively) years after the implementation of the recast [54][9]. An overview of the targets and metrics introduced by the Directive and its recast can be seen in table 1.1. A relative target of 45% (65% respectively) of the average weight of EEE POM over the three previous years replaces the previous absolute collection target (Article 7). Research shows that this target will substantially increase the amount of WEEE that has to be collected. As compared to 2008, the amount of WEEE collected will increase by 50% in 2013 and 100% in 2016 if the targets of the directive are met [79].

Year	Collection Target	Reference
2002-2012	4 kg per person per year	[52]
until 2015	4 kg per person per year OR average amount of WEEE collected in the preceding 3 years (whichever is higher)	[54]
from 2016	45% of the average weight POM in the preceding three years	[54]
from 2019	65% of the average weight POM in the preceding three years OR 85% of WEEE generated	[54]

Year	Recycling and Reuse Target (% of product weight)	Recovery Target (% of product weight)	Reference
2002-2012	50-75%	70-80%	[52]
until 2015	50-75%	70-80%	[54]
2016-2018	55-80%	75-85%	[54]
from 2019*	55-80%	75-85%	[54]

* Based on new WEEE categories

Table 1.1: Overview of Performance Targets set in the WEEE Directive and the Recast of the WEEE Directive

9 The targets gradually increase over a couple of years after the Directive becomes effective.

According to the Directive, producers can opt to fulfill their responsibility individually, which is usually described as 'Individual Producer Responsibility' (IPR). Alternatively, producers may act as part of a collective scheme, which is described as 'Collective Producer Responsibility' (CPR). To date, producers in the EU have typically met their obligations collectively, which has led to the establishment of a large number of collection schemes. Figure 1.1 illustrates the relationship of producers and collection schemes in a CPR system.

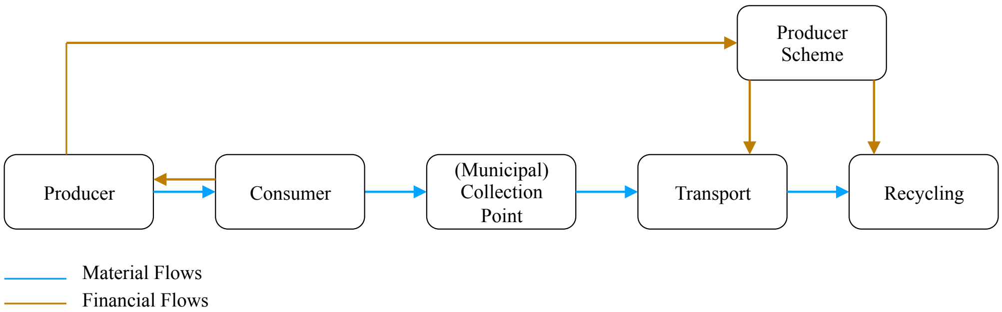


Figure 1.1: WEEE Collection and Recycling in a CPR Setup

The national transposition of the WEEE Directive varies according to member state [136]. In some countries, collection is organized by one collection scheme (e.g. Belgium, the Netherlands), whereas in other countries (e.g. Germany, France) multiple schemes exist to handle product take back obligations on behalf of the producers [105,173]. Manufacturers do not physically have to handle the EOL products they have sold, but are assigned a certain share of the overall WEEE collected and are charged a fee by the scheme they have contracted. The collection system does not discriminate between make/brand and consequently does not reward producers that sell more environmentally friendly products. As a result, and in contrast to the original intent of EPR, there is no evidence that the implementation of the WEEE Directive has motivated more environmentally friendly product design [80]. This and many other concerns related to current EU and national WEEE legislation have been addressed in a number of publications [16,34,80,97,152,194]. Some of the concerns outlined in these studies are:

(1) Some EU member states (e.g. the Netherlands) have implemented a visible fee, which is added to the sale price of EEE in order to provide for the expected cost of collection, recycling and disposal. Such visible fees are criticized as "wrong in principle" because they are considered a compensation for manufacturers at the expense of consumers [34].

(2) The absolute target set by legislation does not motivate higher collection rates and rewards collection of large, heavy EOL products rather than small, lightweight waste. Previous research suggests that targets should include environmental considerations,

rather than being expressed in mass terms. To improve treatment, the authors suggest "material recycling targets" [80].

(3) In countries where competitive producer schemes exist, recycling operations face immense cost-pressure on the one hand and statutory weight based recycling rates on the other. The study of [15] argues that this creates a disincentive for high quality (i.e. high cost) treatment of WEEE (e.g. manual disassembly, depollution), which would be necessary to reach higher recovery rates for certain materials. The author suggests that legislation should address this issue by implementing "Material Recovery Certificates" to maintain high treatment and safety standards.

The debate around producer responsibility in European WEEE legislation is frequently combined with a discussion of the feasibility of IPR [44, 107, 117, 147, 149]. While the term is used in a variety of different connotations, IPR always implies that the responsibility for collection and recycling is assigned to the original producer of an EOL product. The opposite is the current system of CPR, in which EOL products are not assigned to the original producer [147]. Some researchers criticize that the Directive does not incentivize producers to implement IPR. It is suggested that IPR could in fact be a tool for producers to "manage rather than sell their key materials" and create closed material loops [117]. The authors see IPR operationalized in the context of producer owned take back programs. This is a different approach than the one outlined in, for example [149], which discusses IPR in the context of WEEE legislation in Germany. In a CPR system, the share of WEEE assigned to a producer is based on market share; implementing IPR in this system would imply that the amount of WEEE financed by a producer is based on the amount of producer owned WEEE in the overall WEEE stream. The study challenges the feasibility of such a concept in showing that the determination of the individual producer share in the overall WEEE stream requires extensive sorting and statistical analysis [149]. An optimistic view of IPR is expressed in [107], who outlines the system around EOL vehicle legislation in Sweden, which effectively incorporates IPR principles.

1.1.3 Producer Engagement in WEEE Management

The previous chapter has provided an introduction to the issue of WEEE and given an overview of the policy response to the environmental and resource issues associated with EOL electronics. Producers of EEE are legally obliged to provide for financing of WEEE collection and recycling in the EU, but effective WEEE management is also in the interest of industry. In addition to financing of mandatory collection, some OEMs have implemented voluntary WEEE collection programs. Such programs exist in Europe and internationally in order to increase collection rates or to demonstrate commitment to producer responsibility in countries where WEEE legislation does not yet exist [137, 167].

While the collective approach to producer responsibility demands little or even no industry involvement in the physical collection and recycling processes, a number of studies published in previous years show that producers are concerned about the consequences of low WEEE collection rates, illegal export of WEEE, long-term availability of certain raw materials and the effectiveness of EPR in WEEE legislation [73, 74, 116, 167]. While the focus of these studies is diverse, they demonstrate that industry is engaging in WEEE take back beyond legal requirements, and actively participates in discussions around the physical management of WEEE as well as the future relevance of WEEE as a source of secondary raw material supply.

The study of [74], co-authored by a researcher of Motorola Labs, looks at the lifetime of EOL mobile phones and investigates the key motivation of consumers to upgrade to a new and discard of an old phone. The authors of the study are concerned about the environmental impact of unsafe mobile phone disposal and the gap between 'usage lifetime' and 'functional lifetime'. Based on extensive surveying, the study concludes that producers can help to prolong the lifetime of mobile phones by designing the devices in a way that allows for upgrading and functionality extension (e.g. add on cameras). As for EOL mobile phone take back, the study finds that providing convenient collection infrastructure to consumers would increase collection rates. If disposal opportunities were available at a very low effort, consumers would be more likely to send EOL mobile phones to recycling. This finding is confirmed by a recent publication of Nokia's senior sustainability manager [167], which outlines the importance of safe mobile phone recycling and presents the results of several collection programs in various countries. According to the author of this study, producers need to make sure that mobile phone disposal options are convenient for consumers and are suited to the local context (e.g. language, communication of program). The author also highlights that collection programs need to be implemented on a long-term basis in order for mobile phone collection to become a habit for consumers.
A recent publication by the chairman of the environmental board of Hewlett Packard EMEA discusses the availability of key materials for the production of EEE and industry's role in securing supply [73]. Primarily because of the increase of raw material prices over the past ten years and the projected increase in demand for electronic products, the author expresses concerns about the supply of a number of materials critical for the electronics industry. The author suggests that recycling of WEEE is a readily available, flexible source of raw materials, as opposed to accessing primary sources of supply. Producers have very limited possibilities to collect the products they have sold, but they can educate consumers and ensure high environmental, health and safety (EHS) standards in the downstream recycling chain. While this study shows that the environmental and resource implications are a key driver for producers to put WEEE take back on the corporate agenda, another study [116] focuses attention on the impact of EPR on producers in Europe. A case study of Sony Computer Entertainment Europe (SCEE) is presented to illustrate the compliance consequences and producer's challenges under the implementation of the WEEE Directive. The author describes the administrative and compliance

management responsibilities of producers, who need to arrange take back and recycling in 27 EU member states with different WEEE legislation. Because reporting of sales data, auditing, reporting of collected volumes, invoicing and other administrative requirements are rather complex to handle, SCEE has developed an internal strategy to comply with take back legislation in Europe and avoid any cases of non-compliance. The case study outlines that strict compliance tracking is worthwhile because any cases of non-compliance could result in sales blocks, fines or negative media coverage. While it must be acknowledged that all studies represent individual opinions, they provide valuable insights into producer's concerns around WEEE management.

In summary, the key goals for producers to support and initiate WEEE collection and recycling programs appear to be:

- **Compliance with regulation**
- **Resource conservation and environmental impact minimization**
- **Management of corporate reputation**

1.2 Evaluating WEEE Collection and Recycling Programs

In the previous chapter, it was demonstrated that the collection and recycling of WEEE are both a legal obligation and a strategic investment for OEMs. There are risks of non-compliance, but there are also opportunities to make a positive contribution to environmental protection. **But are the existing WEEE collection programs effective and do they contribute to the goals (see subsection 1.1.3) OEMs seem to pursue when initiating these programs? To answer this question, producers need to establish metrics that are informative with respect to their performance in collecting EOL electronics and are guiding producers towards the goals of recycling.** The second part of chapter 1 explains why environmental metrics are important for the electronics industry and outlines criteria that are important for metric development. Existing performance metrics for corporate WEEE collection and recycling programs are benchmarked. Based on the findings of the benchmark assessment and the discussions in chapter 1, the motivation for this thesis is outlined.

1.2.1 Corporate Environmental Performance Metrics

It has often been said that 'if you can't measure it, you can't manage it', meaning that all business activities need to be measured in order to validate achievements and assess progress towards intended goals [8]. While accepted and standardized metrics to assess financial performance exist (e.g. profit for the year, share price, dividend paid to shareholders) [166], the industry is still in the process of developing indicators and metrics to measure environmental performance. Many companies publish information on environmental performance in reports or on corporate websites, supported by a set of metrics, such as energy and water consumption, greenhouse gas (GHG) emissions and amount of post-industrial waste in production. The metric is traditionally normalized because reference values allow for more meaningful comparison and tracking of performance over time [63]. For example, the increase of total GHG emissions generated by a company's operation over a number of years can be a result of the growth of the business (i.e. increased production) or more emission-intensive operations at steady production levels. In this case, it is helpful to relate the emissions to a reference value (e.g. emissions per unit of sales, emissions per EUR/USD of revenue). Over the past years, the industry has also taken up on the metrics and indicators defined by the Global Reporting Initiative (GRI), an organization working in the development of standardized sustainability reporting to facilitate benchmarking of corporate performance with respect to laws, norms, codes and performance standards [85]. GRI indicators include several aspects, i.e. areas that are perceived as vulnerable to industrial activity, such as 'materials', 'energy', 'water' and 'biodiversity'. The latest version of the GRI environmental performance guidelines (3.1) includes indicator EN27 'Percentage of products sold and their packaging materials that are reclaimed by category' [57], an indicator that is theoretically also applicable to WEEE take back and recycling. According to the GRI, the term ‘reclaim’ includes collection, recycling and reuse, but the share of products that is recycled should be reported separately from those products that are reused. The methodology that underlies the indicator is:

$$\% \text{ of reclaimed products } = \frac{\text{products reclaimed within the reporting period}}{\text{products sold within the reporting period}}$$

GRI’s EN27 shows to which extent products sold by the company are collected at EOL and recycled/reused. It appears that the indicator targets the company’s own products, which only partly applies to the current situation of WEEE collection and recycling in Europe. The question is also as to whether the indicator is feasible for products that have a long lifetime, such as EEE. While packaging (e.g. beverage bottles, cardboard) is typically disposed of by the consumer shortly after purchase, the large majority of EEE remains with the consumer for several years. Consequently, there is no realistic possibility for producers of EEE to collect products that were sold within the reporting period, and the GRI indicator is thus not applicable to the electronics industry. The issue of EEE lifetime and reference values for ‘mass collected versus mass sold’ metrics is further discussed in subsection 5.2.1.
Corporate environmental performance metrics are not equivalent to product environmental performance metrics (e.g. energy consumption, amount of recycled material per product), although they are often based on the same goals (e.g. inform customers, quantify and decrease environmental impact) and linked to each other (i.e. good environmental product performance contributes to the overall environmental performance of a company) [122,130]. Environmental metrics for products are frequently implemented following standards or labels, such as the IEEE 1680 standard for environmental assessment of electronic products [89]. Environmental impacts occur beyond the production, use and EOL phase of products and some corporate environmental programs are not directly related to the company’s products (e.g. WEEE collection programs).

Moreover, many companies have metrics in place to compare the environmental performance of different processes, for example in manufacturing or EOL product processing [98, 190]. Process-related performance metrics are helpful to evaluate and compare different processes by measuring e.g. energy consumption, water consumption and material input. Environmental metrics in manufacturing can be part of product-related environmental impact assessments and are particularly relevant for products in which the main life-cycle impact occurs at the production stage. In the context of EOL product treatment, process-related metrics are also relevant to compare different treatment processes and understand e.g. their recovery rates, material input and energy requirements [114]. The differences and linkages between the three types of metrics are illustrated in figure 1.2.

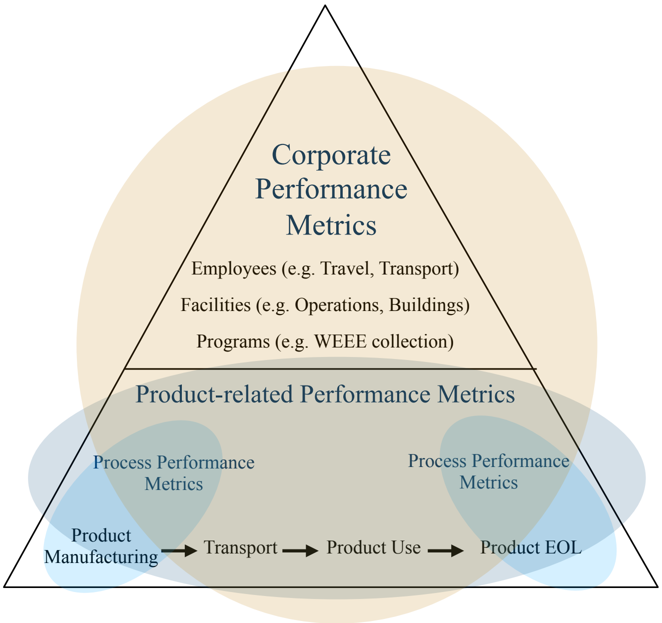


Figure 1.2: Linkage between Product-related, Process-related and Corporate Environmental Performance Metrics

1.2.2 Relevance of Performance Metrics

Establishing informative and effective corporate environmental performance metrics is beneficial for OEMs, for example to:

Assess Performance: Perhaps most importantly, metrics provide information on the accomplishments of environmental programs and help companies understand where they stand [36, 141]. Metrics are also needed to make comparisons against the performance of other companies with similar areas of focus to decrease environmental impacts and comparable environmental programs. In this context, metrics are important to perform benchmarking analyses in order to identify industry best practices [156]. If programs are implemented based on legislation (e.g. WEEE take back programs), companies require metrics to prove compliance and respond to reporting requirements. For legislators, uniform metrics are key to assess and compare the accomplishments of different companies.

Motivate Improvement: Establishing quantitative instruments to measure environmental performance can help corporations to identify areas of potential improvement and structurally work towards set targets [63]. For example, a company aiming to decrease environmental impact in production could assess the current performance in ‘post-industrial waste per unit sold’, consider this as the baseline performance and set a reduction target for a defined point in time in the future. Ideally, metrics are developed in a way that offers guidance on how performance can be improved. Therefore, the analysis of [169] characterizes two types of performance metrics, leading and lagging metrics. Leading metrics assess the parameters that affect the performance and thus provide information on the activities that need to be improved in order to reach better performance. Lagging metrics assess the impact after it has occurred. Lagging metrics are useful to assess current performance, but leading metrics are necessary to motivate improvement.

Achieve Management Buy-in: Environmental protection is typically not perceived to contribute to the economic success of a company and not all managers will want to allocate resources to these programs. Moreover, measures to decrease the negative impacts of industrial activity on the environment in many cases pursue long-term goals (e.g. conservation of freshwater resources, prevent global warming). Long-term goals are challenging to communicate in an environment that measures achievements every fiscal year or quarter. Efforts to build or extend corporate environmental programs require meaningful quantitative measures, to illustrate the effectiveness of these programs and attract funding.

Support External Communication: Many companies have included environmental topics into their communication to consumers and other stakeholders, for example as part of the corporate annual report or in a dedicated sustainability reports [63]. Environmental concerns around a company's business can create negative media attention and potentially influence consumer-purchasing decisions, which is why reporting environmental performance is important for the public image of a company. Metrics can support the credibility of this communication and demonstrate the effectiveness of the industry's efforts to decrease environmental impacts. If corporate environmental performance reporting is supported by a set of meaningful and transparent metrics, companies will not run the risk of being suspected of 'green-washing' or providing ambiguous information (e.g. 'eco-friendly').

1.2.3 Metric Development

A number of previous studies have identified criteria to consider in the development of effective metrics. Some of these analyses define criteria from the researcher's point of view [19, 63, 156], others build on the criteria mentioned in the literature [46, 113, 169]. A comprehensive and structured overview of criteria can be found in the study of [8]. Six criteria were selected from these previous analyses and considered most relevant for this research:

(1) **Useful [19, 156]:** As outlined in the previous paragraph, metrics are a tool for corporations to improve performance and measure progress towards set targets. Before defining metrics, the objectives of the activity need to be well defined and clear so that the metric can be tailored to the objectives. For example, if a company aimed to provide more environmentally friendly packaging for products, the objective could be, for example, to decrease the overall amount of packaging, decrease the amount

of harmful substances or increase the amount of recycled content. While all objectives are covered by the aim to minimize the environmental impact of packaging, each objective needs different metrics to measure progress. If the objective were to decrease the overall amount of packaging per product, mass based metrics would be useful, whereas the toxicity- and material-related objective would require material data and metrics that capture hazardous substance concentration.

(2) **Link to Existing Policy Objectives in terms of Environmental Impact Minimization [63, 113]:** Very closely linked to the definition of goals is the overall relevance of the metric in helping to achieve broadly agreed-upon environmental protection objectives (e.g. conservation of natural resources, increasing resource efficiency). Many of these objectives use general terminology and the industry needs to identify concrete activities, that help achieve these objectives, and metrics that are able to quantify the achievements. If metrics are developed based on existing policy objectives, the corporate programs and activities they evaluate are more likely to be recognized by policy makers and external stakeholders.

(3) **Easy to Use and Communicate [46, 156]:** The most elaborate method to measure performance is useless if it is too complex to be adopted and understood [8]. At the same time, there is a risk to simplify at the expense of usefulness and accuracy. Going back to the previous example of less environmentally harmful packaging, the simplest metric is to measure the mass of packaging per product, but this metric is useless with respect to the objective of harmful substances and recycled content. Overall, the complexity of a metric should always be reasonable. If it is necessary to create complexity, the metric should at least be able to be reproduced as well as transparent in terms of the underlying methodology.

(4) **Feasible in terms of Data Input [46, 156]:** The development of metrics should always be based on the availability of input data and the cost at which this data can be assessed. This criterion might sound obvious, but there is a surprisingly large amount of metrics that are never adopted because they are too data intensive or because the data is too costly to assess. If a metric is too complex in terms of data collection, it will not be adopted over longer periods of time.

(5) **Comparable [8]:** Metrics ideally aggregate information, in that they capture multiple issues of interest and create one meaningful value. However, comparability also implies that a metric is useful for benchmarking. If there is not an official standard for metrics (as it is the case for most corporate environmental performance metrics), the preferred metric for benchmarking is always the one that is adopted by most companies. Because the most popular metric is not necessarily the most useful metric, the criterion itself is slightly ambiguous.

(6) **Diagnostic [8]:** Metrics should also be diagnostic and allow for the identification of cause-effect relationships that result in different metric values. It should always be transparent as to which parameters influence the metric value and how the parameters are linked to each other. If the benefit of metrics is to support companies in improving their environmental performance, it should be clear what parameters determine current performance and which parameters can be influenced to reach better performance.

All of the criteria outlined here will be used to evaluate the current industry metrics (see subsection 1.2.4), as well as the novel metric for corporate WEEE collection and recycling programs, which is proposed in this research (see subsection 5.1.2).

1.2.4 Existing Industry Metrics for WEEE Collection and Recycling Programs

A benchmarking analysis was conducted to investigate and compare how electronics companies currently measure performance in WEEE take back and recycling. The information was obtained from the review of corporate social responsibility (CSR) reports and web pages of 22 OEMs[10]. The analysis is therefore exclusively based on data publicly available. A detailed list of companies, metrics and references is available in appendix A. An overview of the results is shown in figure 1.3.

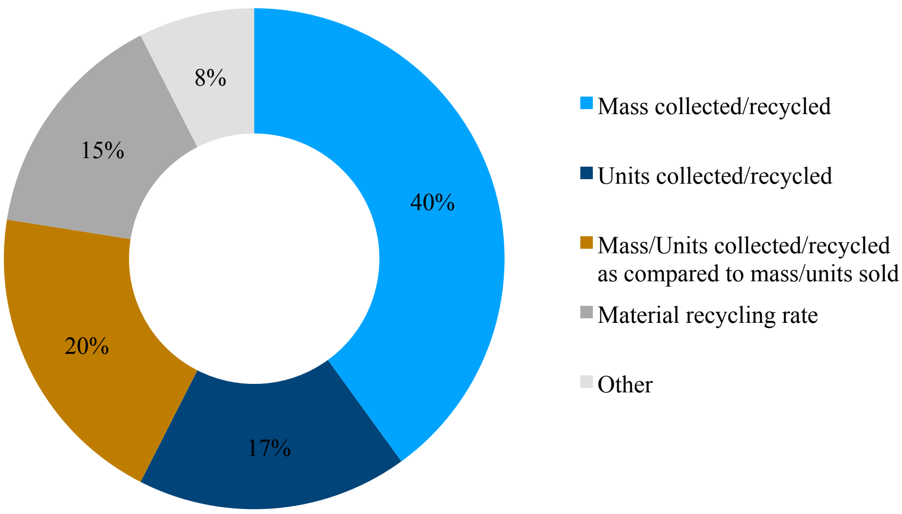


Figure 1.3: Overview of Metrics used by 22 ICT Companies

[10] Not all of the companies analyzed have the same product portfolio, but are either producers of IT, telecommunications or office equipment. Some OEMs have a very diverse product portfolio and cover two or all of these categories. For the purpose of this study, a comparison of these companies is reasonable because all are multinational firms that operate and sell in at least one market where WEEE take back is regulated (e.g. Europe, Japan). It can therefore be assumed that all companies have take back programs in place.

The analysis finds that more than 50% of the corporations that were analyzed communicate weight or units collected and recycled. Most companies do not differentiate between 'collection' and 'recycling', the two terms are used as synonyms. Eight out of 22 companies refer weight/units collected/recycled to the weight/units sold in the same year (e.g. Panasonic, Sony Mobile Communications) or in previous years. If previous sales data serve as a reference point, the metric is based on an estimated average lifetime of the products sold by the company. Some companies assume the same lifetime for all products (e.g. Apple, Sharp), other companies assume different lifetimes for different product groups. Samsung reports that TVs have an estimated average lifetime of ten years, computers are discarded after seven years, and the lifetime of mobile phones is two years. Information referring to the actual recycling of the weight/units collected is reported by six out of 22 companies. Most of these companies report the share of material that is recycled, re-sold, reused or sent to energy recovery and landfills (e.g. IBM, Lenovo). Only two companies (Sanyo, Sharp) disclose information on the raw materials recovered from the collected waste (e.g. amount of secondary copper, ferrous materials, plastics produced). Acer reports "recycling rates", and Fujitsu discloses a "resource reuse rate", but the methodology that underlies the metrics could not be identified[11]. Nokia reports mass of phones and accessories collected, and explicitly points out that the success of EOL product take back and recycling is also measured in the number of countries covered by collection programs and the number of people reached through take back campaigns. Overall, all companies had disclosed at least some information on EOL product take back and recycling on their websites or in dedicated sustainability reports, but some companies disclose much more information than others. The reporting of some companies referred to only one country or region, most companies communicate worldwide data.
As illustrated in figure 1.3 most companies communicate corporate performance in WEEE collection and recycling in mass or unit based metrics. The key reasons for this are:

(a) **Feasibility in terms of data input:** Collection of 'mass' data is easy to collect, as the recycling facility sub-contracted by the OEM or producer scheme will typically weigh the waste prior to processing in order to allocate cost per t. The data is assessed anyway for accounting reasons, and it is convenient to use this data also for external communication of take back achievements.

(b) **Ease of use and understanding:** 'Mass collected' or 'units collected' are easy to understand metrics, which do not require any explanation and can be communicated to a variety of stakeholders. This is contrary to metrics that refer to one or more reference values, such as 'weight collected versus weight sold', a metric, which is based on an estimated average product lifetime and sales data and which requires at least a short explanation of the methodology.

[11] Both types of metrics are allocated to the 'other' category because the information behind these metrics was unclear.

(c) **Legislation:** In countries where WEEE legislation has been enacted, laws incorporate collection targets (e.g. 4 kg per capita in the 2002 WEEE Directive), which typically refer to 'mass' (see table 1.1). Producers have adopted these metrics, as they seem to be based on valid standards and represent current data collection requirements.

1.3 Problem Statement

In light of the previously stated objectives that underlie corporate take back and recycling initiatives (see subsection 1.1.3), 'mass' is an appropriate metric to respond to mandatory reporting requirements. For external communication, mass based metrics are useful because they are easy to understand for a variety of stakeholders and do not need to be supported by any form of methodology or documentation. However, mass/units collected/recycled are not informative metrics with respect to environmental impact minimization and resource conservation. Other than the amount of material diverted from landfills, this type of metric has no direct relation to an environmental objective. Information on the mass or number of products collected neither contains information on the type of material collected, nor is this metric informative with respect to the amount and type of secondary raw materials recovered. In that respect, mass based metrics can even have adverse impacts on the take back strategy of a company because they reward the collection of the heavy products, while the collection of small and lightweight WEEE is discouraged. This is particularly detrimental with respect to the recovery of critical materials as they predominately occur in low concentrations in small WEEE, such as many ICT products. For ICT (which are the focus of this study) and producers of ICT, this means that the collection of e.g. heavy CRT monitors contributes to better performance than the collection of e.g. mobile phones or tablet computers. This is not to say that the collection of monitors is not environmentally worthwhile, but mass and unit based metrics contradict the objective of increasing collection rates for small WEEE and the recycling rates of critical materials [26, 64]. What further impairs the effectiveness of mass and unit based metric is that they are informative with respect to the achievements in collection, but do not cover the process of subsequent recycling. Mass and unit based metrics are not data intensive, also due to the fact that data assessment does not capture the full EOL path of the waste and in fact stops at a very early stage of WEEE management.

With respect to the criteria that metrics should be based on (subsection 1.2.3), 'mass/ units collected/ recycled' are only partly useful to achieve the goals of recycling (criterion 1). Mass and unit based metrics are helpful to report to legislators and prove compliance, but fail to guide producers in optimizing take back and recycling with regard to environmental impact minimization. In fact, current metrics may even lead to decisions that are counter-productive to environmental impact minimization (criterion 2). On the other hand, current metrics are easy to use and communicate, and do not require much data

input (criterion 3 and 4). This facilitates implementation over a longer period of time and thus enables year-on-year comparison of performance. Current metrics are comparable in that they enable benchmarking of best performance in amount of WEEE collected and recycled (criterion 5), but they are not diagnostic with respect to the system they are analyzing (criterion 6). With the current metrics in place, companies can only improve performance if they collect more waste, but the metric does not guide producers in improving any other relevant aspects of WEEE collection and recycling programs.
Overall, the existing metrics do not help producers to achieve the general objective of using WEEE as a source of raw materials and optimizing the established collection and recycling systems towards environmental impact minimization. If producers of electronics are the ones who are made responsible for WEEE collection and recycling, producers also need to implement more effective metrics to measure achievements and motivate improvements in both WEEE collection and recycling.

1.4 Research Questions

The motivation for this research is based on the fact that mass and unit based metrics to evaluate corporate WEEE collection and recycling programs are not effective and not informative with respect to the environmental impact of WEEE take back and recycling. Existing metrics largely originate from reporting obligations that industry needs to fulfill in countries where WEEE legislation has been enacted. As existing metrics were not explicitly defined to address the environmental goals of corporate take back and recycling programs, limitations and shortcomings of these metrics are evident and may constrain performance improvement. If companies do not have the tools to evaluate the environmental impact of recycling, they will not reach the goal of maximizing the environmental benefit of recycling. More meaningful metrics are required to evaluate existing programs and to develop future programs around the objective of environmental benefit rather than increase of mass collected.

The central question of this research is:

(1) How can producers measure the performance of WEEE collection and recycling programs, irrespective of mass and units collected?

Because environmental objectives are perceived to be a fundamental driver of EOL product recycling, the second question is

(2) How can producers incorporate environmental indicators into alternative performance metrics?

The objective of this research is to develop an alternative approach to measure corporate achievements in EOL product take back and recycling, which is informative with respect to the environmental impact of recycling and diagnostic with respect to performance improvement. Chapter 1 will develop a methodology that responds to the research questions outlined above and the research gaps identified in existing studies. The methodology will be validated in chapter 3 and chapter 4, both through an empirical experiment and a scenario analysis. The proposed metric will be discussed in chapter 5 and compared against the objectives of this research, as well as the metric criteria outlined in chapter 1. The methodology that underlies the proposed metric, as well as the methods that were used to collect and analyze empirical and literature data, will be explained in the respective sections of this thesis.

2 Methodology

The following chapter presents a methodology to evaluate the performance of WEEE collection and recycling programs in view of environmental impact minimization. Previous research dealing with process performance metrics and corporate performance metrics is summarized. It is shown how existing environmentally weighted metrics can be influenced by numerous variables in the material recovery system. A methodology is proposed, which considers process recycling rates and the individual avoided environmental burden (AEB) of different materials. The development of this metric is based on Substance Flow Analysis (SFA) methods. The following part of this research also covers a number of environmental impact assessment methods that can be combined with the proposed metric methodology.

2.1 Literature Review

There are a number of studies that have proposed metrics to evaluate performance of recycling processes, but few studies have investigated alternative metrics to assess OEM performance in WEEE collection and recycling programs. The following chapter reviews the existing research according to its area of application (evaluation of recycling process and recycling system performance versus evaluation of corporate environmental performance), the scope of the analysis (recycling system versus recycling process) and the proposed indicators (environmental versus economic). Studies on process performance metrics include [77], who develops the 'Quotes for Environmentally Weighted Recyclability' (QWERTY) method, which combines the environmental and economic performance of different recycling scenarios into one tool and allows the optimal recycling route for different kinds of WEEE to be assessed. QWERTY employs processing cost and material yields as economic indicators, and Eco-Indicator'99 points as indicators of environmental performance[12]. Economic, as well as environmental performance is compared against the performance of the best and worst case scenario in terms of cost/revenue and environmental gain/burden, respectively. Economic indicators to evaluate the cost-effectiveness of recycling processes are also analyzed by e.g. [40, 66, 108, 154]. While all of these studies use secondary material yields, recovered value, and process costs as indicators of economic performance, the scope of the system they are analyzing is diverse. Some authors look at the recycling system as a whole (including cost for transport and logistics), e.g. [66,83,108] and [38], while other studies focus on the processing operation exclusively, e.g. [40,119,154]. Extensive research has also been carried out by [182] who incorporates data on the characteristics of process feed material (i.e. product design data) into a recycling process

[12] Eco-Indicator'99 is an impact assessment method that allows for the calculation of eco-indicator scores for materials and processes based on LCA inventories, the calculation of damage on human health, ecosystem quality and resources and a weighting methodology [60].

model. To evaluate process performance, [182] employs recovered mass per substance, as well as the quality of the recyclate as performance indicators. In terms of evaluation of environmental performance of recycling systems and processes, [114] uses energy consumption, energy-related air emissions and solid waste generation as indicators of system performance. Environmental indicators to describe recycling process and system performance also include the work of [187] who assesses the environmental performance of the WEEE disposal system in Switzerland by comparing the environmental impact (expressed as Eco-Indicator'99 points) per t of collected WEEE against the environmental impact of two theoretical baseline scenarios (incineration/energy recovery, landfilling). Another study considering the environmental impact of WEEE recycling is the study of [83], who proposes 'recovered energy' as an indicator of environmental system performance. 'Recovered energy' links to the recovered mass in a recycling process and compares the energy required for the primary production of a material to the energy required to produce the same mass of the exact material from secondary sources. 'Recovered energy' is further elaborated by [8] who investigates the use of the "energy-weighted mass recovery index" in the context of corporate performance metrics and shows that 'recovered energy' is a meaningful indicator to evaluate the environmental performance of recycling facilities. The study of [8] is particularly relevant to this research as it is shown that the 'recovered energy' indicator can be used as a tool to analyze corporate environmental performance[13]. For example, the 'recovered energy' approach was adopted by [2] to calculate the CO_2 savings of a large recycling operation in Germany. One of the few studies investigating alternative metrics for EOL product collection and recycling programs is [128], who builds on the work of [8] and proposes the "value-retention" indicator as a tool to evaluate the economics of respective corporate programs. However, [128] does not discuss environmental indicators. Table 2.1 provides an overview and categorization of the research reviewed in this chapter.

Process and System Performance				**Corporate Performance**	
Recycling System		**Recycling Process**			
Environmental	Economic	Environmental	Economic	Environmental	Economic
[38], [77], [83], [114], [187]	[38], [66], [77], [83], [108]	[77]	[40], [119], [154], [182]	[2], [8]	[128]

Table 2.1: Overview of Existing Research on Metrics and Indicators to assess Recycling Process and Corporate Program Performance

Also relevant to this research are studies investigating the recyclability of substances as it is considered to be a decision factor for recovery efforts [184]. Some studies propose value as an indicator of material recyclability [94, 184], while [39] proposes the relationship of substance mixing and substance value as an indicator of material recycling potential. As one of the few studies to consider environmental characteristics of materials, [94] presents

[13] In this case: corporate environmental performance of recycling facilities.

the weighted environmental impact (based on the Korean Eco-Indicator) method of a substance as a suitable recyclability indicator[14]. Overall, it can be concluded that there is a variety of previous studies that provide useful tools and metrics to assess the performance of recycling processes and systems and the recycling potential of substances embedded in EOL products. There are, however, very few studies that investigate the issue of effective metrics for take back and recycling programs from the perspective of OEMs. Among the main research gaps are:

Operational Feasibility: Although methodologically and technically helpful, the research to date has not yet provided tools to convey the scientific knowledge on best recycling practices to OEMs who have increasing influence over how products are collected and recycled[15]. The key challenge lies in designing metrics that useful and diagnostic, in order to motivate corporate action on take back and recycling. Few, if any of the available studies provide tools and methodologies that are able to bridge scientific knowledge and corporate decision-making.

Metric Sensitivity: There is a clear gap in the perception that metrics need to trigger performance improvement on the one hand, and the lack of research on how metrics need to be designed to show improvement potential on the other. Research to date has provided valuable insights on the performance of processes/systems from a snapshot perspective, but does not adequately show which variables in the system are sensitive to change. Focusing on the present moment is a first step of any environmental impact analysis, but it is equally (if not more) important to show strategies for improvement.

Environmental Impact: No studies appear to have investigated tools to measure the environmental performance of WEEE take back programs from an OEM perspective. The study of [128] provides an effective metric to address the economic performance of OEM take back programs, and [8] and [83] investigate 'recovered energy' as a feasible indicator to measure the environmental impact of recycling, but none of the existing research provides an environmental measure to assess the performance of take back and recycling programs from the perspective of OEMs.

All of the studies discussed in the previous paragraph are useful for the investigation of a methodology that helps electronics manufacturers to measure the environmental impact and the effectiveness of WEEE take back programs. The first objective of the methodology is to combine corporate performance measures and recycling process metrics. The second objective is to incorporate the major variables of material recovery and their interactions into an analysis of metric performance improvement. The third objective is to quantify the environmental impact of take back and recycling programs.

[14] The Korean Eco-Indicator is an environmental impact assessment method, which was funded by the Korean government and further developed by e.g. [103] to support impact assessment of industrial activities in Korea.

[15] For a detailed description of the problem statement and motivation for this research see Thesis Structure.

2.2 Building the Methodology

The 'recovered energy' approach explored by [2, 8, 83] is used as a starting point to build the proposed methodology. Upon analysis of this approach, the metric is broken down into the different variables that influence recovered mass and energy, and SFA methods are used to show the relationship of these variables. To increase the diagnostic value of the metric with regard to resource consumption, a set of alternative environmental impact assessment methods is combined with the 'recovered energy' approach.

2.2.1 Problem Definition

$E_{recovered}$ (recovered energy) is defined as the difference between the energy required to produce primary material and the energy required to recycle the exact material from waste [83]. In this study, the term 'primary material' is used for material produced from virgin sources (e.g. metals ore), while 'secondary material' describes material, which is recovered and recycled from EOL EEE. Energy consumption is considered as an indicator to quantify the environmental impact of primary and secondary materials production. Other environmental indicators will complement energy consumption later on in this research.

$$E^i_{recovered} = m^i(E^i_p - E^i_s) \tag{2.1}$$

where E_p is the energy required to produce a substance from virgin sources
E_s is the energy required to produce a substance from secondary sources
i is a substance
m is the mass of a substance

$E_{recovered}$ thus can be described as an "environmentally weighted mass recovery metric" [8] because it is based on the process (mass) yield. The methodology caters this study well in that the overall focus of the analysis is on recycling of metals from WEEE (see subsection 1.1.1), which are able to regain their original quality and properties in recycling processes. Recycled metals are thus able to perfectly substitute primary metals [184]. In applying the methodology to an OEM's WEEE take back and recycling program, data needs to be assessed on the amount and type of substances recovered from the collected WEEE. To calculate the total $E_{recovered}$, the total amount of 'recovered energy' from n substances is calculated by applying (Equation 2.1).

$$E_{recovered} = \sum_{i=1}^{n} m^i(E^i_p - E^i_s) \tag{2.2}$$

Once $E_{recovered}$ has been assessed, the question remains as to how present performance can be improved. The approach of traditional mass based metrics is that recycling programs improve as more WEEE is collected. This contradicts the 'recovered energy' methodology, which can be influenced by numerous variables in the recycling system.
To analyze the sensitivity of the variables in (2.2), Material Flow Analysis (MFA)/ SFA methods are used. SFA is a specific kind of MFA that is based on the same parameters and principles as MFA but emphasizes that an analysis deals with substances rather than goods [23]. The following terms are defined: a **substance** is a chemical element or a compound (e.g. gold, cadmium). **Goods** combine numerous substances into an economic entity of matter (e.g. glass, plastic, concrete). **Materials** are substances and goods, without differentiation[16]. SFA is a method to track and quantify the flows of one or multiple substances through a defined system. Examples of a **system** are for example, a geographical area, a sequence of process steps in an industrial plant or a body of water. The underlying principle of this method is the first law of thermodynamics, which constitutes that mass and energy are indestructible entities, which can be transformed and diluted, but never destroyed. In other words, the amount of a substance entering a system always equals the amount that remains within the system boundaries and/or is exported [23]. **Stocks** are defined as any remainder of a substance in the system, e.g. steel in buildings or copper in cell phones that are in use. Within a process or a system, **mass transfer coefficients** (TC) describe the rate at which a substance is transferred in the output flow [9]. For example, if there are no stocks in a process, the TC is 1 as the mass of the input flow(s) equals the mass of the output flow(s).
Figure 2.1 shows the basic variables and interrelations that are of concern in an SFA analysis.

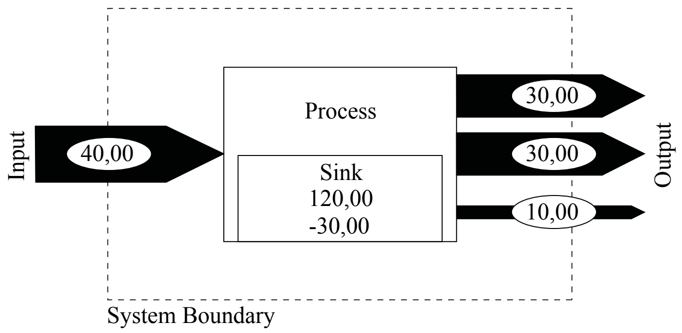


Figure 2.1: Simplified Illustration of Material Flow Analysis Variables

[16] The terms 'material' and 'substance' are used in accordance with the common definition in MFA/SFA in this research. The term material is used liberally, referring to substances (e.g. gold) and goods (e.g. plastics). However, in the context of the sensitivity analysis, as well as in the empirical trial, the terms 'substance' and 'SFA' are used because flows of certain elements in a recycling process are described.

Previous research around WEEE recycling has employed SFA and MFA, e.g. [31,121,162,179]. There are few standards available for SFA, but [23] and [9] propose several steps to be followed in any SFA analysis: (1) problem definition, (2) system definition, (3) modeling and data collection, and (4) interpretation. Similar to other scientific analysis, it is important to define the goal of the SFA to inform the focus and scope of the analysis. The second step includes the definition of the substance(s) that is (are) of interest in the analysis, the processes that are included, as well as the definition of the system boundary. The data inventory includes data on substance flows, e.g. in- and output flows to the system, stocks within the system boundary, substance concentrations in flows and stocks, and data uncertainties. Flow models are able to show the interrelations between the different variables in the system. The final step in an SFA analysis is the interpretation of the results. According to [143], this is an important (but often neglected) step, as SFA should be used as a tool to guide decision-making. This research puts specific emphasis on the interpretation step as the results of the SFA are used to inform the sensitivity of the metric. The goal is to understand which variables behind $E_{recovered}$ can realistically be influenced by OEMs in order to increase the environmental effectiveness of WEEE take back programs.

2.2.2 System Definition

An illustration of the system within which this methodology operates is shown in figure 2.2.

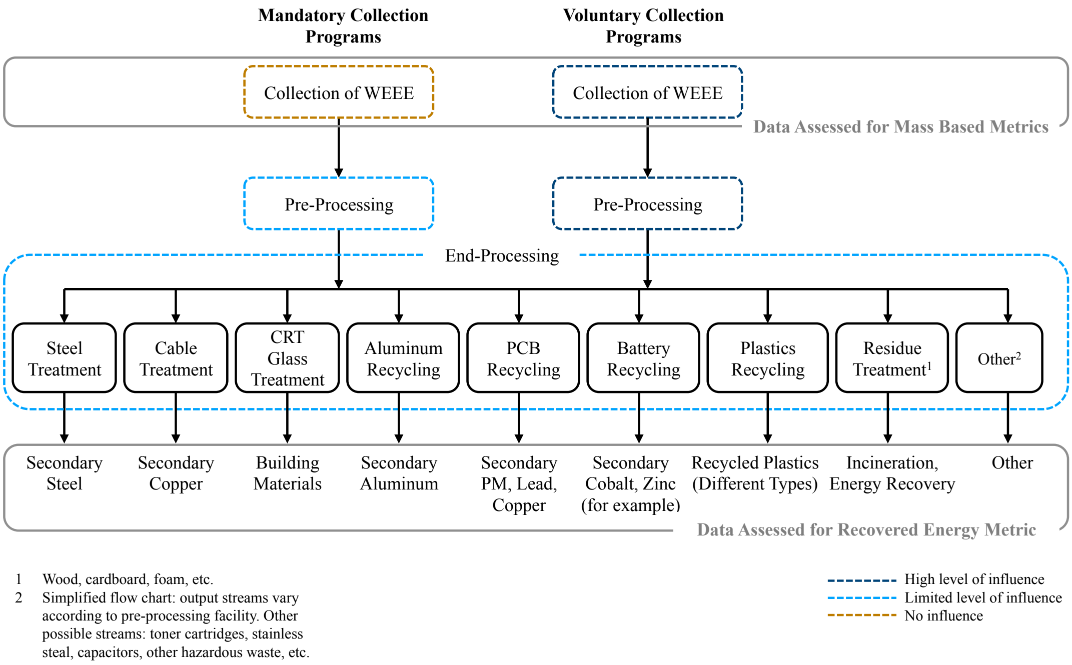


Figure 2.2: Simplified Diagram of Material Flows Relevant for 'Recovered Energy'

This figure displays the perspective of OEMs when assessing data on collected WEEE and the materials that are reclaimed in the recycling process. The WEEE is collected from consumers and then transported to a pre-processing facility, followed by a number of end-processing facilities that treat the output streams of the pre-processing facility. The mass of recycled material ready for use in a new application can be assessed after end-processing.

OEMs in Europe engage in two different types of collection programs, mandatory programs (legal obligation, WEEE collected by municipalities) and voluntary programs (no legal obligation, WEEE directly collected by the OEM) (see Figure 2.2). Depending on voluntary and mandatory programs, OEMs have different levels of influence on the collection process, the selection of a pre-processing facility, the downstream recycling processes and other mechanisms (e.g. energy input to production processes) in the system. The following chapter gives a detailed overview on the system variables, which build $E_{recovered}$. Regarding access to data and influence of OEMs on the system variables, some estimations are made based on the system description in figure 2.2.

2.2.3 System Variables

Five variables, which define $E_{recovered}$ are identified: mass prepared for recycling, energy input to recycling process, energy input to primary material production process, substance, process recycling rate. The mass of a substance reclaimed in a recycling process is determined by the mass that was fed to the process and by the recovery rate of the process.

$$E_{recovered} = \sum_{i=1}^{n} (M_{in}^{i} k^{i})(E_{p}^{i} - E_{s}^{i}) \tag{2.3}$$

where M_{in} is the mass fed into the process
k is the recycling rate of the process

Mass Prepared for Recycling (M_{in}): The mass of a substance fed to a process determines the mass that can potentially be reclaimed. Even if the other variables in the system do not change, collecting and preparing more WEEE for recycling presents a strategy to reach higher metric performance.

Energy Input to Recycling Process (E_s): The amount of energy required to recycle a substance from waste depends on the energy input to the recycling process (e.g. energy input to machinery, furnace, smelter) and the rate at which waste is processed. With respect to the impact on the 'recovered energy' metric, the energy input to the process impacts the $E_{recovered}$ score in that the difference between E_p and E_s increases as E_s decreases.

That is, assuming constant values for all other variables (including the amount of WEEE prepared for recycling), $E_{recovered}$ increases with recycling processes becoming less energy intensive. The energy input to recycling processes is considered at the inventory stage of materials life cycle assessment (LCA). Provided that data on any decrease of process energy requirement can be assessed, $E_{recovered}$ values increase as E_s values decrease. For this study, predefined E_s values are accessed through the ecoinvent database (see subsubsection 2.2.4.2) and one dataset is selected for each secondary material (see appendix D). If the inventory of these datasets were to be revised in the future, any decrease in energy input to the recycling process would influence E_s and thus $E_{recovered}$. Energy input to recycling processes cannot be influenced by OEMs, as the operation of the recycling facility falls under the responsibility of the operator of the recycling facility.

Energy Input to Primary Material Production (E_p): Producing metals ready for application in electronics requires mining and preparation of ores, smelting and refining [33]. Similar to the energy intensity of recycling processes, the energy input to primary materials production impacts $E_{recovered}$ in that the difference between E_p and E_s increases as E_p increases. Assuming constant values for all other variables, higher $E_{recovered}$ performance is reached with primary material production becoming more energy intensive. For this research, primary materials datasets are selected from the ecoinvent database based on a number of criteria (see appendix D). Realistically, OEMs have no control over the energy input to production of primary materials as there is no direct relationship with primary materials producers.

Process Recycling Rate (k): The recycling rate of a process describes the rate at which the mass of a substance fed to the process can be recovered. In even the most technologically advanced recycling scenario, not all materials get 100% recycled. For example, a metallurgical copper smelting process is able to recover copper, some PM and other materials at a $>90\%$ recycling rate, but will not recover ferrous metals [181]. Recycling rates are substance and process specific, and can range from 0% to almost 100%. In considering the efficiency at which materials are reclaimed, higher m^i and $E_{recovered}$ values can be reached, even if M_{in} and all other variables in the system remain constant. This can be observed in table 2.2, which illustrates the recycling rates of three processes and their impact on $E_{recovered}$ performance.

For this comparison it was assumed that the same mass and material composition of PC PCBs are processed in three different recycling scenarios. Data on the composition of PCBs, estimated recycling rates of different EOL scenarios and the individual 'recovered energy' for four substances were combined. Scenario A involves light shredding of PCBs, Scenario B describes intense shredding of PBCs, both followed by a metallurgical process. In Scenario C, the PCBs are directly treated in a metallurgical process (no shredding).

Input to Scenario A, B and C		
Substance	Weight share in input material [69]	Total Weight (kg per t of PCBs)
Aluminum	5.00%	50.0
Ferrous	7.00%	70.0
Copper	20.00%	200.0
Gold	0.03%	0.3
Total	**32.03%**	**320.3**

Scenario A (Light shredding followed by metallurgical process)		
Recovery rate [181]	Recovered mass (kg)	Recovered CED (MJe)
80.00%	40.0	5,482.4
90.00%	63.0	1,244.1
40.00%	80.0	1,696.2
10.00%	0.0	7,073.6
	183.0	**15,496.4**

Scenario B (Intense shredding followed by metallurgical process)		
Recovery rate [181]	Recovered mass (kg)	Recovered CED (MJe)
90.00%	45.0	6,167.7
90.00%	63.0	1,244.1
50.00%	100.0	2,120.3
10.00%	0.0	7,073.6
	208.0	**16,605.7**

Scenario C (No pre-processing followed by metallugical process)		
Recovery rate [181]	Recovered mass (kg)	Recovered CED (MJe)
0.00%	0.0	0.0
0.00%	0.0	0.0
90.00%	180.0	3,816.5
95.00%	0.2	67,199.1
	180.2	**71,015.6**

Note: Recovered CED values are based on data obtained from ecoinvent v2.1

Table 2.2: Process Comparison of Recovered Mass and Energy: Light Shredding, Intense Shredding and Metallurgical Processing of 1t of PC PCBs

The recovery rates are based on extensive modeling of recycling scenarios elaborated by [181][17]. It is shown that the most favorable scenario in terms of mass yield, does not reach the best $E_{recovered}$ performance, as high recovery rates for copper and gold can be reached in process C. Comparing the worst and best-case scenario in terms of $E_{recovered}$, scenario C reaches 4.5 times the performance of scenario A. Scenario B recovers more mass than the other recycling scenarios, but Scenario C recovers 4.2 times more energy than Scenario B. Recycling rates of different processes do not fall under direct control of OEMs, but can be considered when contracting recycling operations as downstream vendors for WEEE take back programs.

Substance (i): As the energy required for primary production and recycling differs according to substance, $E_{recovered}$ shows different values for each substance. An electronics manufacturer that would try to increase $E_{recovered}$ without changing other system parameters could prioritize substances with high $E_{recovered}$ over substances with lower $E_{recovered}$ for recycling. OEMs have some influence on this system parameter as they can select the recycling facilities and hence the preferred processes for the treatment of collected EOL equipment. Furthermore, OEMs can set up take back programs for the collection of products that contain comparably high amounts of substances with high $E_{recovered}$ values.

[17] The recycling rates shown in table 2.2 possibly deviate from the actual values to a minor degree because the data was taken off a plot published in [181].

The description of system variables and the process comparison in table 2.2 reveals the main difference between the proposed methodology and traditional mass based metrics. In using mass based metrics, corporate environmental performance (or take back program performance) can only be improved if the quantity of WEEE collected and recycled increases. As the 'recovered energy' approach is coupled to the process recycling rates, as well as the environmental 'footprint' of individual substances, performance can be improved even if the amount of WEEE collected remains constant. From an OEM perspective, this approach is not only interesting in terms of program cost (collecting more WEEE always generates higher cost), but also from a resource efficiency standpoint. Overall, it is shown that the 'recovered energy' approach depends on numerous variables in the recycling system. OEMs have influence over some of the variables, which build $E_{recovered}$. There is a potential for OEMs to draw attention to the recycling rates of processes and the environmental footprint of substances when initiating take back programs and choosing recycling vendors/processes.

2.2.4 Data Input

Two types of data can be varied in the methodology: absolute values for all variables, which define the methodology (k, E_p, E_s, M_{in}, i) and thematic values, i.e. alternative environmental impact indicators to 'energy input'.

2.2.4.1 Absolute Values

Process Recycling Rates (k): A number of studies have investigated recycling rates for different substances in different WEEE recycling processes. Consequently, this data is available from literature and covers a couple of different processes, for example manual pre-processing [43, 181], mechanical pre-processing [31, 119, 151, 181] and some metallurgical processes [17, 51, 77, 181]. Reliable data on process recycling rates is in fact difficult to obtain due to rapid development of new recycling technologies, as well as changes in the composition and product design of WEEE. Collecting empirical data on the recycling rates of a process is complex and requires operators of recycling facilities to disclose information that is otherwise proprietary. As a part of this study, such empirical data was collected in a recycling trial, which is described in chapter 3.

Mass Prepared for Recycling (M_{in}): Data on the mass of substances prepared for recycling is difficult to obtain for the mixed WEEE stream, but less so for OEMs if EOL products of the own brand are recycled. If data on the material composition of these products is available from the company's engineering records, characterizing the amount and type of substances put into a recycling process is feasible. This is also true if the feed material consists of only one type of product (e.g. cell phones, PCBs) regardless of brand, because a representative sample can be obtained and the substance composition of the waste can be chemically analyzed prior to recycling [69]. Data on the exact mass of a substance present in the mixed WEEE stream is difficult to assess because WEEE presents a very heterogeneous waste stream. The material composition of products also varies according to age, type and brand [78]. Literature data on the material composition of different electronics shows high variability (see appendix B). A robust approach to deal with this issue is developed and extensively described in [31], who assays and analyzes all 24 output fractions of a recycling process for PM, ferrous, aluminum and copper content. In [31] the sum of the substances identified in the output fractions represents the estimated input to the process. For the purpose of this study, a cost/benefit decision was made and four output streams of the recycling trial described in section 3.2 were chemically assayed. This provides sufficient data to validate the metric methodology. An estimation of the material composition of the mixed WEEE stream and the recycling trial feed material is illustrated in appendix B and appendix C.

Substances (i): Generally, all substances, which can be recycled from waste without loss of quality and properties can be selected for the methodology. This does not apply for all materials in WEEE (e.g. plastics), but applies for ferrous and non-ferrous metals. Furthermore, the selection of substances should always be based on the availability of data and the purpose of the investigation. For this analysis, six substances were selected. The two metal categories, which are typically recovered from WEEE are non-ferrous metals (e.g. copper, PM, aluminum) and ferrous metals [161]. Despite their low mass content in WEEE, **gold, silver** and **palladium** (along with other PM such as rhodium) are the most significant substances in terms of value recovery per recovered mass [37]. Other non-ferrous metals that are included in this analysis are **copper** and **aluminum**. Copper is recovered in the same final recycling process as PM (see subsubsection 3.2.1.2), so it is reasonable to assess this substance along with gold, silver and palladium. Aluminum is separated in the pre-processing step of WEEE recycling and treated at an aluminum smelter (see subsubsection 3.2.1.2). Ferrous metals represent a major mass stream in electronics and WEEE recycling, which is the reason why ferrous metals were investigated in this study. **Ferrous metals** account for 63 to 69% of the weight of a desktop PC [59, 175], and account for over 40% of the weight in 1 t of mixed WEEE [30].

2.2.4.2 Thematic Values

In a first step, the methodology is tested with 'energy input' to primary and secondary production values. However, 'energy' has been criticized as an insufficient stand-alone environmental impact indicator [3, 75]. In order to provide a more comprehensive view on the avoided impact on natural resources (e.g. energy sources, biologically productive land), human health (e.g. toxicity) and climate change (e.g. greenhouse gas emissions), several alternative indicators and life cycle impact assessment (LCIA) methods are applied. These include single-score indicators, which quantify the direct consumption of available resources (e.g. energy and exergy extraction from the natural environment, land use), as well as "impact-oriented" [135] indicators, which describe the life cycle impact of a specific material on the environment (e.g. on the climate, human health, freshwater). The 'recovered energy' metric can thus be translated into an 'avoided environmental burden' (AEB) metric.

$$AEB = \sum_{i=1}^{n} (M_{in}^{i} k^{i})(EB_{p}^{i} - EB_{s}^{i}) \tag{2.4}$$

where AEB is the 'avoided environmental burden'
EB_p is the environmental burden resulting from the production of primary material
EB_s is the environmental burden resulting from the production of secondary material

The main source of data is ecoinvent (version 2.1), a database for LCA issued by the ecoinvent centre[18]. The database includes several LCIA methods, of which some are applied to the proposed methodology. The ecoinvent centre provides detailed information on the methodology and scope of the inventory, which are useful in case multiple datasets are available for one product [33]. An overview of the information and assumptions on which the selection of datasets was based is given in appendix D.

For all primary metals the scope of the inventory includes (1) mining of the ore, (2) processing (e.g. sorting, leaching) of the ore, and (3) metallurgical processing of the ore concentrate into primary metal. Transportation of primary metal from the refinery/plant to any given location is not included[19]. Transportation of the ore to the plant, as well as transportation between different production sites and other input materials to the plant is included in the datasets. Just like for primary metals, the scope of the inventory of secondary metals data is limited to the material production processes only, which comprises the mechanical pre-processing process (i.e. shredding and sorting) and the downstream metallurgical recycling process [33]. Transportation of the secondary material to any given location is not included. The selected dataset 'shredding, electrical and electronic scrap' (GLO) is a generic dataset for mechanical treatment of WEEE (regardless of WEEE type) and comprises the energy consumption of the pre-processing machinery, air emissions originating from the shredding process, impacts originating from the building infrastructure (indirect impacts) and transport from the collection site to the pre-processing facility.

[18] The ecoinvent centre is a consortium of universities and research institutes led by Eidgenössische Technische Hochschule (ETH) Zurich, École Polytechnique Fédérale de Lausanne (EPFL) Lausanne, Swiss Federal Laboratories for Materials Testing and Research (EMPA), Swiss Federal Research Station Agroscope Reckenholz-Tänikon (ART) and Paul Scherrer Institute (PSI) [4].
[19] For this study, datasets 'at refinery' or 'at plant' are selected.

Transportation between the pre-processing facility and the end-processing plant is covered in the datasets for secondary materials. This choice of inventory boundaries avoids the complications and data uncertainties associated with the transport of primary and secondary materials to different locations for application in products. A detailed discussion on transport activities in the context of this study can be found in section 2.3. The inventory boundaries for both types of materials (primary and secondary) are illustrated in figure 2.3.

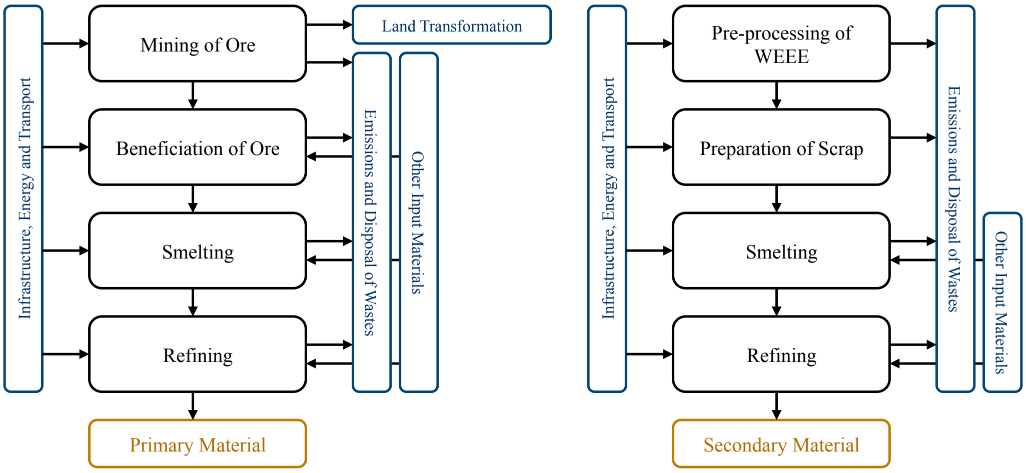


Figure 2.3: Inventory Boundaries for Primary and Secondary Materials Production

The following paragraphs give an overview of the LCIA methods and data, which were used in this study: Renewable and non-renewable Cumulative Energy Demand (CED), renewable and non-renewable Cumulative Exergy Demand (CExD), Ecological Footprint (EF), Global Warming Potential (GWP) (IPCC 2007, 100a), Human Toxicity Potential (HTP), Acidification (AP) and Nutrification Potential (NP) (CML 2001).

Cumulative Energy Demand: Many studies suggest that the cumulative fossil energy demand greatly increases the environmental impact of products [75]. The CED method assesses all direct energy demand (e.g. energy demand of production processes) as well as indirect energy demand (e.g. energy demand of buildings and production infrastructure) throughout the life cycle of a commodity or service [3]. CED values are expressed in MJ-equivalents (MJe/kg). Ecoinvent provides eight CED categories for different sources of energy. This is based on the fact that each energy carrier can be attributed an intrinsic energy value, which is based on the amount of energy removed from the natural environment [3]. There is no aggregated value available in the database, but it is possible to combine and adjust all renewable categories and non-renewable categories for own calculations. Energy values for non-renewable and renewable resource categories are shown independently in table 2.3 because some of the main studies on CED recommend refraining from aggregating non-renewable and renewable energy sources in CED analyses [56].

Substance	Non-renewable CED for production of primary material (MJe/kg)	Non-renewable CED for production of secondary material (MJe/kg)	Recovered non-renewable CED (Mje/kg)
Aluminum	159.9	22.9	137.1
Copper	48.5	27.3	21.2
Ferrous Metals	29.1	9.3	19.7
Gold	289,965.3	7,021.8	282,943.5
Palladium	169,264.8	13,432.7	155,832.0
Silver	6,088.2	121.8	5,966.4

Substance	Renewable CED for production of primary material (MJe/kg)	Renewable CED for production of secondary material (MJe/kg)	Recovered renewable CED (MJe/kg)
Aluminum	34.0	1.8	32.2
Copper	11.9	1.7	10.3
Ferrous Metals	1.9	0.5	1.4
Gold	22,454.8	417.9	22,036.9
Palladium	7,422.7	790.8	6,631.9
Silver	610.4	7.3	603.2

Substance	Total CED for production of primary material (MJe/kg)	Total CED for production of secondary material (MJe/kg)	Total recovered CED (MJe/kg)
Aluminum	194.0	24.7	169.3
Copper	60.4	29.0	31.5
Ferrous Metals	30.9	9.8	21.1
Gold	312,420.1	7,439.7	304,980.3
Palladium	176,687.5	14,223.6	162,464.0
Silver	6,698.6	129.0	6,569.6

Table 2.3: Renewable and Non-renewable CED Values for Selected Primary and Secondary Metals

Overall, CED is referred to as an impact indicator with low technical data uncertainty, compared to other methodologies [3, 75].

Cumulative Exergy Demand: CED describes the amount of energy withdrawn from nature in order to provide a commodity or service, but does not capture the quality of the energy that is consumed. The 'quality of energy' is linked to the second law of thermodynamics, which defines that not all of the inherent energy of a system (e.g. 1t of coal, 1 l of hot water) is useful to perform work. The amount of energy that is available to do work is defined as 'exergy' [10]. Exergy is therefore the maximum amount of work that can be performed by an energy flow or a mass with reference to the conditions of the environment [42], and is frequently referred to as "useful" energy [46]. In the context of environmental analysis, exergy is a common unit to assess the energy efficiency of systems, for example of waste treatment/recycling processes [47, 88, 134] and production processes [20, 188]. In acknowledging the fact that exergy (unlike energy) can be destructed or consumed, measuring the exergy of systems has also been suggested as a tool to quantify resource consumption [10]. Understanding the loss of exergy that appears in the course of material and energy transformation (i.e. resource consumption), allows for the identification of processes that potentially contribute to resource depletion[20]. In an effort to integrate a perspective on resource consumption into the metric methodology, 'exergy demand' is proposed as an alternative indicator to 'energy demand'. The method employed is CExD, which is extensively discussed in [21] and integrated into the ecoinvent database. Similar to CED, the CExD method takes into account the total amount of exergy consumed (i.e. withdrawn from the natural environment) to provide a commodity or service. Ecoinvent defines ten resource categories (fossil, nuclear, primary forest, metals and minerals as non-renewable sources; wind, solar, water, biomass and water as renewable sources), which are each attributed an intrinsic exergy value, expressed in MJ-equivalents (MJe/kg).

Substance	Non-renewable CExD for production of primary material (MJe/kg)	Non-renewable CExD for production of secondary material (MJe/kg)	Recovered non-renewable CExD (MJe/kg)
Aluminum	168.8	23.1	**145.8**
Copper	260.9	32.7	**228.2**
Ferrous Metals	38.2	9.4	**28.8**
Gold	695,435.7	7,112.7	**688,323.0**
Palladium	184,665.9	13,522.2	**171,143.7**
Silver	12,530.2	123.4	**12,406.8**

Substance	Renewable CExD for production of primary material (MJe/kg)	Renewable CExD for production of secondary material (MJe/kg)	Recovered renewable CExD (MJe/kg)
Aluminum	48.0	3.3	**44.7**
Copper	21.8	3.6	**18.2**
Ferrous Metals	3.2	1.1	**2.1**
Gold	56,421.5	801.8	**55,619.7**
Palladium	34,769.0	1,948.5	**32,820.5**
Silver	1,215.5	13.9	**1,201.5**

Substance	Total CExD for production of primary material (MJe/kg)	Total CExD for production of secondary material (MJe/kg)	Total recovered CExD (MJe/kg)
Aluminum	216.9	26.4	**190.5**
Copper	282.7	36.3	**246.4**
Ferrous Metals	41.4	10.5	**30.9**
Gold	751,857.2	7,914.5	**743,942.7**
Palladium	219,434.9	15,470.6	**203,964.3**
Silver	13,745.7	137.3	**13,608.3**

Table 2.4: Renewable and Non-renewable CExD Values for Selected Primary and Secondary Metals

[20] A related approach is discussed by [62], who proposes entropy production as a measure of resource consumption.

A major asset of CExD is that it also accounts for non-energetic resources, such as water resources and metals, which makes it a more informative method for resource consumption analysis than CED. The inclusion of non-energetic resource categories is particularly valuable in the context of a study dealing with metals, as CExD shows the contribution of metal ores (almost 40%) to the total exergy consumption of metals [21]. This demonstrates that CExD is not only useful to compare the 'exergy intensity' of different commodities (such as primary versus secondary metals), but also to compare the exergy values of different resource categories (for example energetic and non-energetic resource categories) within one data set. As in CED, renewable and non-renewable CExD datasets are shown independently in table 2.4[21].

Ecological Footprint: The EF concept was introduced by [144] as a tool to assess the anthropogenic impact on the Earth's resources. The concept quantifies the amount of biologically productive land, which is required to produce the resources consumed by a population and absorb emissions generated by the consumption of non-renewable energy carriers. Ecological Footprint is a common methodology to assess and compare the environmental impact of regions, countries and other geographical entities [189]. In the context of LCA, the EF is a method to assess the amount of direct and indirect land occupation over time. Indirect land occupation originates from the use of nuclear fuels, fossil fuels and cement burning [76]. These processes are included into the calculation by estimating the size of the afforestation area required to offset CO_2 emissions from fossil fuel use, cement burning and nuclear fuels. Ecological Footprint datasets are integrated in ecoinvent. The values are expressed in m^2a (occupation of m^2 land per year). The method is interesting to explore in the context of the metric methodology since previous research has shown that the primary production of metals shows high EF values ($> 10^4 m^2a$) as compared to low EF values of recycling processes ($0.05 m^2a$)[22].

Substance	Total EF for production of primary material (m2a/kg)	Total EF for production of secondary material (m2a/kg)	Recovered total EF (m2a/kg)
Aluminum	32.2	4.2	**28.0**
Copper	10.8	5.9	**4.8**
Ferrous Metals	5.6	1.7	**3.9**
Gold	58,525.0	2,506.3	**56,018.7**
Palladium	31,790.0	2,852.8	**28,937.2**
Silver	1,260.0	43.2	**1,216.8**

Table 2.5: EF Values for Selected Primary and Secondary Materials

[21] For a detailed discussion on the complications associated with aggregating values for renewable and non-renewable energy sources, please refer to [21].

[22] The study compares EF values for a set of 19 categories (e.g. recycling, incineration, transport, plastics, paper) [76].

However, when comparing 98 metals, the variance of the individual values in the metal category is high compared to other categories [76]. For this analysis 'total ecological footprint' (GLO) values were sourced from the ecoinvent database. Table 2.5 shows the EF values selected for the metric analysis.

Global Warming Potential (IPCC 2007): Carbon dioxide (CO_2) is the most important anthropogenic GHG. The concentration of CO_2 and other GHGs (e.g. methane, nitrious oxide) in the atmosphere has been steadily increasing since the start of the industrialization, mainly due to the use of fossil fuels and land use change. GHG emissions cause a rise in global temperature levels along with a series of impacts on e.g. the natural environment, regional climate and availability of natural resources [90]. GWP (IPCC 2007) in ecoinvent is a method to quantify the GWP of goods and substances, i.e. the amount of GHG emissions caused along the life cycle, in order to understand their impact on climate change. GHG emissions considered in the inventory are converted into CO_2e emissions based on their GWP as compared to CO_2 [3]. The method captures direct GHG emissions (e.g. from the use of fossil energy carriers), as well as emissions due to land transformation (e.g. deforestation) and biogenic emissions. Ecoinvent provides three different categories with respect to average GWP for a specific period. For this study, values from the 100 year (a) impact category were selected (IPCC 2007, 100a). GWP is a straightforward impact oriented indicator, which provides the metric methodology with a widely accepted impact unit (CO_2e). The GWP (IPCC 2007) values used for the metric analysis are shown in table 2.6.

Substance	GWP originating from production of primary material (kg CO2e/kg)	GWP originating from production of secondary material (kg CO2e/kg)	Recovered GWP (kg CO2e/kg)
Aluminum	12.4	1.4	11.0
Copper	3.2	1.8	1.3
Ferrous Metals	2.1	0.5	1.6
Gold	18,695.0	851.5	17,843.5
Palladium	9,729.4	756.8	8,972.6
Silver	439.2	14.7	424.5

Table 2.6: GWP (IPCC 2007, 100a) Values for Selected Primary and Secondary Materials

Human Toxicity Potential, Acidification, Nutrification (CML 2001): The CML 2001 method covers a number of impact-oriented assessment categories, of which human toxicity, acidification and nutrification are selected to inform the E_p and E_s variables [3]. The human toxicity category captures the impact of a large number of toxic substances on the human environment (e.g. air, soil, freshwater, seawater) [68]. For each product, the HTP is expressed as 1,4-dichlorobenzene (DCB) equivalents per kg (kg $1.4 - DCBe/kg$). For this study, a category fitted to an infinite time horizon and global application was selected (HTP infinite, GLO). The AP of substances describes the impact of acidifying substances (e.g. ammonia, nitrogen oxides, sulfur dioxide) on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). Acidification can cause e.g. degradation of soil, damage to woodlands and decrease of fish populations. The acidification potential (AP) of a product is expressed as sulfur dioxide (SO_2) equivalents per kg (kg SO_2e/kg) in ecoinvent [68]. Nutrification includes all impacts resulting from excessive emissions of nutrients (especially nitrites and phosphates) to air, water and soil [61]. Nutrification causes many negative impacts on ecosystems, e.g. excessive phytoplankton growth. The NP of products is expressed as phosphate (PO_4) equivalent per kg (kg PO_4e/kg) in ecoinvent. For this study, the generic datasets (no specific time scale) and global scale application were selected for both AP and NP (AP/NP generic, GLO). Together with the GWP method, the CML 2001 categories evaluate the consequences of primary and secondary materials production, and go beyond the accounting approach of CED, CExD and EP. Table 2.7 shows the HTO, AP and NP values selected for this analysis.

Substance	**HTP originating from production of primary material (kg 1.4-DCBe/kg)**	**HTP originating from production of secondary material (kg 1.4-DCBe/kg)**	**Recovered HTP (kg 1.4-DCBe/kg)**
Aluminum	57.9	1.4	**56.5**
Copper	641.9	8.4	**633.5**
Ferrous Metals	10.6	0.8	**9.8**
Gold	392,150.0	647.2	**391,502.8**
Palladium	17,475.0	328.8	**17,146.2**
Silver	4,451.4	11.2	**4,440.2**

Substance	**AP originating from production of primary material (kg SO2e/kg)**	**AP originating from production of secondary material (kg SO2e/kg)**	**Recovered AP (kg SO2e/kg)**
Aluminum	0.1	6.2E-03	**4.8E-02**
Copper	0.5	2.0E-02	**0.5**
Ferrous Metals	8.5E-03	2.2E-03	**6.2E-03**
Gold	192.6	1.8	**190.7**
Palladium	8,538.5	3.1	**8,535.4**
Silver	6.7	3.2E-02	**6.7**

Substance	**NP originating from production of primary material (kg PO4e/kg)**	**NP originating from production of secondary material (kg PO4e/kg)**	**Recovered NP (kg PO4e/kg)**
Aluminum	6.1E-03	1.8E-03	**4.3E-03**
Copper	0.5	1.1E-02	**0.5**
Ferrous Metals	2.0E-03	3.6E-04	**1.6E-03**
Gold	1,067.0	0.1	**1,066.9**
Palladium	16.1	3.8E-01	**15.7**
Silver	12.5	2.2E-03	**12.5**

Table 2.7: HTO (infinite), AP (generic) and NP (generic) Values for Selected Primary and Secondary Materials

2.3 Discussions

In the previous chapter it was shown that comparing the environmental burden of primary metals production with that of secondary metals production is a robust methodology to assess avoided environmental impact, as primary materials data consistently show higher EB values than recycled metals data. The analysis of the AEB methodology and the investigation of alternative environmental impact indicators revealed some challenges and opportunities that are worthwhile to discuss.

The number of datasets for primary metals is generally much higher than the data available for recycled materials. Especially for the 'critical metals' (see subsection 1.1.1) (e.g. indium), there are no datasets for recycled metals. This data needs to be assessed in the future to enable the inclusion of these materials into environmental impact analysis. For some recycled metals, the available data is not tailored to WEEE recycling. For example, the dataset for 'palladium, secondary, at refinery' describes the recycling of secondary palladium from automotive catalysts. This is the best dataset on secondary palladium currently available and it is reasonable to use this data in the context of this study [177], but datasets describing secondary raw material recycling from WEEE would be convenient. At the time this study was completed, an LCA of a precious metals refinery in Europe was ongoing, but no material specific data appeared to be published [159]. Such analysis is valuable for the future inclusion of more data on secondary metals (from WEEE) into the ecoinvent database.

Furthermore, the development of a 'criticality' method, which aggregates aspects such as scarcity, estimated future demand and supply into one indicator would be a useful future scientific endeavor. This study considers exergy demand as an indicator of natural resource consumption, which is a widely accepted and informative method. However, CExD is only an indirect way to capture resource issues and does not capture any of the 'criticality' aspects mentioned in subsection 1.1.1.

The inventory boundary of the selected datasets covers the primary and secondary production processes, but does not include transportation from the end-processing facility to a manufacturing plant. Although transportation (especially air transportation) can substantially impact the environmental footprint of products, it is neither feasible, nor useful to include this part of the material life cycle into this study. Above all, the study does not deal with a showcase example of material recycling versus primary materials production for a specific case. In the context of studies investigating the benefits of recycling in a specific region or for a specific case [67, 187] it is of course essential to include more transportation activities. This study aims at developing a baseline methodology for OEMs to assess the environmental benefits of collection and recycling programs in any given location, potentially even for the total mass of WEEE that was collected globally in one year.

The material flows of recycled metals after end-processing are unclear because recycled metals can usually not be distinguished from primary metals. End-processing facilities sell metals to multinational trading companies [140], who trade primary and secondary metals alike. Consequently, it is not feasible to 'locate' secondary metals and track the material flow up to the re-application in a new product in order to calculate the transportation that was necessary to provide the recycled metal for manufacturing. For this methodology and the potential area of application, it is reasonable to limit the scope of the data inventory to production processes (extraction from virgin ore/waste, processing and refining in a sequence of primary production/recycling steps) because the boundaries can clearly be defined, which makes the data for primary and secondary production comparable.

Another aspect that concerns the data is that of limited quantitative information on data uncertainty. On the basis of ecoinvent background reports some qualitative statements can be made. The single score methods (CED, CExD, EF), as well as the GWP method show low data uncertainty compared to the CML 2001 methods, because many estimations need to be made at the impact assessment stage [3]. This is particularly true for toxicity impact assessment methods (e.g HTP), which need to be further developed [58]. While there is a need to refine the information on data uncertainty and develop the quality of toxicity methods, it also needs to be said that this study sourced data from the most comprehensive and transparent database currently available.

The previous chapter has illustrated that the AEB methodology provides by far more insight into the recycling system than the traditional mass based metric. It also motivates OEMs to improve take back programs with respect to environmental impact minimization. The limits of using the metric are in including those materials into the data assessment, which do not regain their original quality in recycling [184]. This can be illustrated with the example of recycled plastics, which can only completely substitute primary plastics if different types (e.g. ABS, PVC, PC) and colors (e.g. white, black) can be recovered separately from the WEEE. In reality, this is rarely the case for the mixed WEEE stream, and is only feasible if large amounts of one specific type of product are treated in one batch. In most cases, the mixed recycled plastics from WEEE will not be used in the same type of product from which they were recovered.

Another question that arises is that of the allocation of the benefits of recycling to OEMs [55]. A recycling company might argue that the stakeholder in charge of the actual recycling process should be credited the environmental benefit of material recovery (like in the case of a large recycling company in Germany [2]). Others might argue that the same is true for the legislators, who initiate recycling policies and targets, and provide some of the infrastructure for WEEE collection. Manufacturers of EEE will support that they should be credited the AEB, because they are financially liable for the take back and recycling. In fact, any stakeholder initiating WEEE take back and recycling programs (e.g. charities collecting EOL phones) could claim the credit to themselves. It is important to note that it is not the purpose of this analysis to allocate the AEB to any stakeholder in the recycling system, nor credit OEMs for the avoided environmental impacts and resource consumption that originate from WEEE recycling. The aim of the metric methodology is simply to provide an informative and effective measure to OEMs to assess the performance of take back and recycling programs and motivate actions beyond increase of collected mass.

2.4 Conclusions

The previous chapter has shown that the proposed AEB metric can be influenced by several variables in the recycling system. It was further shown that energy consumption as an indicator of environmental impact can be complemented by a number of alternative environmental indicators, which provide a more comprehensive view on the avoided resource consumption and environmental impacts resulting from the recovery of secondary materials. All of the impact methods that were reviewed show particularly high AEB values for PM, compared to ferrous metals, copper and aluminum. However, it also has to be considered that these materials cover only a small amount of the total mass of the WEEE stream. The absolute AEB values of materials always have to be evaluated in connection with mass flows. This kind of analysis will be outlined in chapter 3. The previous chapter has demonstrated options to improve metric performance by outlining the influence of the main system variables on AEB. In doing so, it was shown that the methodology is not only helpful to assess current program performance but also to give OEMs guidance on how collection and recycling programs can be improved in the future.

3 Empirical Case Study

To demonstrate the validity of the proposed methodology, a base case of WEEE recycling is considered. The case deals with the recovery of secondary raw materials from waste ICT equipment, which are collected through municipal collection points and then treated at a pre-processing facility. The key objectives of the case study are

(1) to investigate which products are currently collected in the ICT waste category,

(2) to quantify the amount of secondary raw materials recovered from ICT waste, and

(3) to provide a proof of concept for the proposed metric methodology.

For the purpose of this case, sampling analysis of ICT waste, as well as a physical recycling trial is conducted at a pre-processing facility in Europe. Previous empirical WEEE recycling trials compare the impact of different recycling technologies (manual disassembly versus mechanical pre-processing) on material yields [151] and analyze material flows and recovery yields of precious metals in a WEEE pre-treatment process [31, 43]. A study by [120] carries out a recycling trial to investigate material flows of organic compounds, heavy metals and other materials in a WEEE pre-treatment process. The analysis by [123] performs revenue and cost analysis of mechanical pre-treatment of WEEE. Overall, recycling trials provide a valuable tool to collect original data on process recovery rates and raw material yields. These data points are critical for the assessment of the performance of recycling processes (e.g. with respect to mass yields and AEB) but often inaccessible due to confidentiality concerns of the operators of recycling facilities. As in the aforementioned studies, the trial applies SFA methods (see subsection 2.2.1) to assess the flow of substances within the pre-processing stage of WEEE recycling. The approach chosen for this case study is original in that:

(1) Specific emphasis in put on the proportion of product categories in the trial feed material, which consists of waste ICT equipment. The share of each product category in the trial feed is allocated according to the results of the preceding sampling analysis;

(2) Data assessment in the recycling trial is limited to the amount of data necessary to test the validity and effectiveness of the proposed metric methodology, i.e. the trial elaborates SFA for only some substances. The case study is premised on two theoretical assumptions. One concerns the feed material of the trial, which is representative of the waste ICT equipment collected through municipal collection in Europe in 2011. The other relates to the recycling process reflecting a standard process to mechanically process WEEE and separate shredder scrap into a number of output fractions.

3.1 Waste Characterization

The case study is designed to enable generalizations about the overall ICT waste collected and recycled. In order to generalize, the composition of the trial feed material must be representative of the composition of the overall ICT waste[23]. Representativeness can be assumed if the proportion of different products in the trail feed material reflects the proportion of products in the overall ICT waste stream as accurately as possible. ICT waste in this analysis includes any ICT equipment that has been disposed of at a municipal collection site and which coincides with one of the product categories listed in table 3.1.

Sampling Category	Definition
Personal computer (PC) monitor	Personal computer monitor based on cathode ray tube (CRT) technology
Flat panel display (FPD) monitor	Personal computer monitor based on liquid crystal (LC) or plasma technology
Desktop PC/server	Plastic or metal case enclosing the data processing hardware of a PC/server (tower and desktop models), excluding monitor and other accessories
Laptop/notebook/netbook	Personal computer for mobile use, which contains a monitor, a keyboard and a pointing device
Printer/fax/scanner/multifunctional	PC peripherals used to print, fax or scan data (laser and inkjet technology)
IT misc.	Modem, router
IT accessory	PC mouse, PC keyboard
Mobile phone	Portable phone
Phones (other)	Fixed phone (landline use)

Table 3.1: Product Categories for Sampling Analysis

Information on the current product mix can be obtained either through existing data, or empirical data collection. However, there are few data points available on the product composition of the WEEE in general and ICT in particular, and the available data is not useful in the context of this study. Some data is provided by 'Schweizerischer Wirtschaftsverband der Informations-, Kommunikations- und Organisationstechnik' (SWICO) [165], a scheme responsible for ICT and consumer electronics (CE) waste take back in Switzerland, 'Stiftung Elektro-Altgeräte Register' (EAR), an organization in charge of WEEE management in Germany [164] and ICT Milieu, the producer take back scheme in the Netherlands [87].
Table 3.2 shows that EAR and SWICO include take back statistics for CE (e.g. audio equipment, televisions) in their reporting, product categories that are not within the scope of this study[24]. With respect to the level of detail in defining the product categories, the data available from EAR, SWICO and ICT Milieu cannot be translated into the categories defined in table 3.1. For example, the existing data does not report different types of monitors, while this study distinguishes between FPD and CRT monitors.

[23] In this context, the term 'composition' describes 'the mix of products' (e.g. share of monitors, printers, desktop PCs).
[24] Excluding CE from the calculations was not possible, because EAR did not publicly disclose absolute tonnage numbers.

Category	NL, 2010 (%)	CH, 2010 (%)	DE, 2010 (%)
Source	**[87]**	**[165]**	**[164]**
Monitors	58.8	13.5	23.8
Personal computers/servers/laptops	19.5	10.3	8.9
Printing/scanning/copying equipment	14.1	17.3	9.5
Telecom	0.5	3.7	1.0
IT accessories	7.1	6.5	-
Televisions	-	29.3	42.7
Foto/video	-	0.2	0.1
Dental	-	0.1	-
Consumer electronics	-	19.2	14.1
TOTAL	**100.0**	**100.0**	**100.0**

Table 3.2: 2010 Take Back Statistics for ICT and CE Waste in the Netherlands, Switzerland and Germany

Another aspect that must be considered is shown by [7], who clearly illustrates that the proportion of product categories within ICT waste undergoes considerable changes over time. At the time this study was designed, the existing data from EAR, SWICO and ICT Milieu was already one year old and considered to be somewhat outdated. To conclude, it is necessary to collect empirical data on the current composition of the ICT waste stream in order to prepare a representative mix of feed material for the recycling trial.

3.1.1 Methodology

Because the overall waste stream is too large to be studied, samples serve as a base for inferences about the population. The validity of the inferences depends on how closely the proportion of product categories in the overall number of samples represents the proportion of product categories in the overall ICT waste stream.

Only few studies have previously dealt with the collection of this type of empirical data and investigated the representativeness of the results [102,132,149]. The analysis of [149] builds on guidelines for the preparation of scientifically credible sampling established by [102]. These guidelines are helpful in preparing samples for chemical analysis (e.g. toxicity tests) but do not address the type of sampling analysis that is carried out in this study. The guidelines also give some information on sampling of containers, which is discussed in subsection 3.1.3. More useful in the context of this study is the analysis by [132], which quantifies the representativeness of the WEEE sampling results carried out by SENS, the scheme for WEEE (excl. ICT and CE) take back in Switzerland. In order to investigate the share of eleven WEEE categories in the WEEE stream, SENS conducts sampling analysis at recycling facilities. Because each sample is characterized based on the product category, the basic assumption of [132] is that the analysis of representativeness must be based on the number of units (not the overall weight) sampled. A confidence interval (CI) is determined for each WEEE category, which gives an indication on the accuracy of the estimated value (share of a category in the overall population). This study applies a sampling methodology similar to the one elaborated by [132]:

(1) Random samples are taken from the overall population. In random sampling, each unit theoretically has an equal probability of being included in the sample [27].

(2) Dichotomy applies to every category, i.e. one sample is attributed as either 'category' or 'non-category' [132].

(3) As a large number of samples are characterized in the analysis, the results (share of each category) are considered representative of the overall population [132].

(4) Errors in the total sample follow a normal distribution because of the large number of samples. The standard error $\sigma(p_x)$ for each category share can be expressed as follows [27]:

$$\sigma(p_x) = \sqrt{\frac{\pi_x \times (1 - \pi_x)}{n}} = \frac{\sqrt{\pi_x \times (1 - \pi_x)}}{\sqrt{n}} \tag{3.1}$$

where n is the number of samples and
π is the estimated share of the category in the total sample.

$\sigma(p_x)$ is inversely proportional to $\sqrt{n}$ [110]. However, the standard error (and thus the reliability of a category share) does not depend on the size of the overall population the samples are taken from.

(5) Assuming that the sample proportions are normally distributed, the 95% confidence intervals are calculated by multiplying the standard error with the standard normal deviate:

$$CI_x = \sigma(p_x) \times \pm 1,96 \tag{3.2}$$

The upper confidence limit is thus $\sigma(p_x) \times \pm 1,96$ above π_x, the lower confidence limit $\sigma(p_x) \times \pm 1,96$ below π_x. The difference between the upper and the lower confidence limit is defined as the absolute CI width.

(6) Because the reliability of an estimated value not only depends on the absolute CI width but also on the size of the value itself, the relative CI is calculated:

$$CIR_x = \frac{CI}{\pi} \tag{3.3}$$

CIR_x describes the relationship of the absolute CI width to the estimated value, which is helpful to understand the absolute uncertainty of the results.

3.1.2 Results

The waste was accessed at the recycling facility hosting the subsequent recycling trial[25]. A total of approximately 30 t of waste ICT equipment was randomly drawn from the incoming shipments to a recycling facility in Europe. The samples were drawn over two subsequent weeks in July 2011. The samples were drwan from different shipments to ensure that multiple municipalities were covered by the analysis. Each waste ICT unit (sample) was hand sorted and categorized according to the categories listed in table 3.1. A total number of 5,233 units were categorized, weighed and registered.

Category No.	Category	Units	Total Weight (kg)	Unit (%)	Absolute CI Width (%)	Relative CI	Uncertainty (%)
1	PC monitor (CRT)	810	11,696	15.5	2.0	0.1	12.7
2	Flat panel display (FPD)	152	678	2.9	0.9	0.3	31.3
3	Desktop PC/server	862	8,250	16.5	2.0	0.1	12.2
4	Laptop/notebook/netbook	78	213	1.5	0.7	0.4	44.1
5	Printer/fax/scanner/multifunctional	1022	6,419	19.5	2.1	0.1	11.0
6	IT misc.	214	66	4.1	1.1	0.3	26.3
7	IT accessory	1871	1,497	35.8	2.6	0.1	7.3
8	Mobile phone	101	9	1.9	0.7	0.4	38.6
9	Phones (other)	123	85	2.4	0.8	0.3	34.9
	TOTAL	**5,233**	**28,913**	**100.0**			

Table 3.3: Results of Sampling Analysis and Uncertainties

The data was finally consolidated; the total weight and number of units per category were converted to percentages to assess the share of each category in the overall number of samples. Table 3.3 shows the results of the sampling analysis, including statistical uncertainties[26,27].

Those categories with a large share in the overall number of samples show uncertainties $< 20\%$, whereas categories with a smaller share (e.g. category 8) show uncertainties $> 20\%$ and up to 44%. For categories 2, 4, 6, 8 and 9, taking more samples would increase the representativeness of the sampling results. Other than the distribution of units across the

[25] Specifications on the location of the facility cannot be disclosed in this study to protect the identity of the facility operator. This does not compromise the validity of the sampling methodology, which is reproducible in another geographic setting.

[26] The results of the sampling analysis showed some inconsistencies regarding the total weight of some categories (6 IT misc., 7 IT accessory, 8 Mobile phone) and the number of units in these categories. It is likely that these inconsistencies are due to errors in the sampling process, i.e. the sorter incorrectly categorized samples. It is unlikely that these errors are due to weighing mistakes. The errors could not be reproduced at the time they were detected, so the number of units was corrected based on an estimate for the average weight of the respective product types.

[27] The sampling analysis showed that many of the products in category 5 were broken into pieces due to unloading and shifting of the container. To correct this error and avoid double counting, all samples categorized as 'Printer/fax/scanner/multifunctional' showing a weight less than 2 kg (6% of the total number of samples), were excluded from the final data set.

overall number of samples, table 3.3 also shows the distribution of weight across the total volume sampled for the analysis. Based on weight, this distribution shows the highest value for category 1, as CRT monitors were the heaviest products in the product mix[28]. In addition to data acquisition, the sampling process showed that many of the samples had been liberated from valuable parts prior to arrival at the recycling facility. This was mainly noticeable for products with metal cables (mostly copper) on the outside, which can easily be cut off. According to the operator of the pre-processing facility, an estimated 60% of WEEE arriving at the facility has already had cables, other metal parts and functional units (e.g. hard drive, main logic board) removed during the collection process. For the recycling business, this results in substantial financial damage because of the loss of metals, while only the less valuable materials (e.g. plastics, glass) remain for processing at the plant. In the context of this study, the 'cannibalization' of the samples was primarily an issue because the sampling analysis was followed by a recycling trial, which required complete products to be processed.

3.1.3 Discussions

The output of the sampling analysis is a set of up-to-date and well-documented results on the product composition of the ICT waste stream. The statistical analysis provides reliable, quantitative estimates of the representativeness of these results. Overall, the methodology to determine representativeness is a feasible and useful approach. In addition to the statistical analysis, comparison with the results of previous sampling analysis illustrates the representativeness. The sampling results obtained in this study were compared with the results of a pilot sampling analysis that the operator of the pre-processing facility had undertaken over the course of six months in 2011. The total amount sampled equaled 375 t. For this pilot analysis, the recycler had drawn random sample containers from the incoming waste shipments and the content was characterized according to five product categories. The data from the sampling analysis performed in this study was fitted to these categories to compare the results of the two analyses.

Product Category	**Pilot Study Results % Weight**	**Sampling Study Results % Weight**
1	46.6	42.8
2	34.4	34.7
3	18.9	22.2
4	0.1	0.3
5	<0.1	<0.1
TOTAL	**100.0**	**100.0**

Table 3.4: Comparison of Sampling Results with Results of Pilot Sampling Analysis

[28] The weight of each category is irrelevant for the statistical reliability assessment of the sampling results, however, this data was useful for the recycling trial that followed the sampling analysis.

Table 3.4 illustrates that the difference between the results of this sampling study and the recycler's pilot analysis is small, although the amount of waste sampled and categorized was over 12 times larger in the pilot analysis. This finding also supports a conclusion of [132] in showing that there is no correlation between the number of samples and the size of the overall population. Discussions with different stakeholders in the recycling business revealed that the amount of samples taken is often fixed to the weight of the total WEEE stream (e.g. 1% or 2% of the total mass of WEEE processed at the facility is sampled). This approach is also supported by the sampling guidelines in [102], which recommend that 300 containers need to be sampled if the overall population is larger than 600 containers. In this study, it is shown that a much smaller number of sample containers are sufficient to achieve representative results on the share of different product categories in ICT waste. Taking more samples certainly increases the reliability of sampling results, but above a certain number of samples the reliability of the data improves only marginally [132]. Especially with regard to the high cost of sampling analyses, it important to note that the number of samples taken does not have to be increased as the overall WEEE processed increases.

Some limitations that this study had to deal with are the sampling period and the geographical coverage. Ideally, samples were taken from all municipal collection sites in the country, which was not possible because the collected waste is processed by several recycling companies. The pre-processing facility only receives only a certain share of the WEEE from municipal collection points. There is also a possibility that the composition of the product mix shows temporal variability over the course of the year, so taking samples from January throughout December is usually favored[29]. Furthermore, systematic uncertainties need to be considered due to the practical nature of this study. The sampling was planed carefully around the conditions on site (e.g. sampling period, access to waste, geographical coverage), but systematic errors may occur during the implementation of a sampling plan. In this case, false categorization of samples, double counting of samples or other deviations from the original sampling plan could have occurred as the analysis progressed on site. All errors identified were discussed in the preceding section.

The results of the sampling are a robust base for the composition of the feed material for the recycling trial. On the basis of the statistical analysis and comparison with previous sampling results, it can be concluded that the share of product categories in the trial feed represents the composition of the overall ICT waste stream.

[29] In their study, [132] show that distribution of different WEEE categories varies over the course of the year. For example, IT and CE products show higher return rates in January and February, which may be due to increased sales of IT and CE products during the holiday season.

3.2 Recycling Trial

The recycling trial includes the physical pre-processing of ICT waste and the modeling of downstream end-processing steps for some material streams. The overall aim of this trial is to reconstruct a baseline scenario, which illustrates the current situation of WEEE recycling. The final results of the trial must provide information on the type and quantity of secondary raw materials recycled from a representative mix of waste ICT equipment. Furthermore, the analysis is designed to identify and quantify potential material losses in the recycling process. This data serves as a base to validate the usefulness of the proposed methodology. The main outputs of the trial are:

(1) **Assessment of Actual Secondary Raw Material Yields:** The output of the physical trial is a list of material output streams, which are characterized and weighted. After the pre-processing, all of the output fractions need to be further processed in metallurgical processes to produce secondary raw materials. The end-processing of aluminum scrap, ferrous materials, PCBs and copper/PM (Cu/PM) rich scrap is modeled based on literature data. The output of the modeling step is data on the type and amount of secondary aluminum, copper, steel, gold, silver and palladium recovered from the ICT waste. The empirical/modeled results of the trial can then be evaluated with the AEB metric.

(2) **Assessment of Potential Secondary Raw Material Yields:** Assuming that the rate at which materials are recovered in the trial is improvable, the study analyzes the material flows of aluminum, copper, ferrous, gold, silver and palladium to identify potential material losses. The methodological framework supporting this part of the research is SFA (see subsection 2.2.1). Samples are taken from three trial output streams and are chemically assayed. If losses of aluminum, copper, ferrous, gold, silver and palladium are identified, the impact of these losses on the AEB metric can be shown.

The recycling trial was conducted in August 2011 at the same recycling facility as the sampling analysis. Prior to the trial, 30 t of complete waste ICT products were put together based on the distribution of product categories assessed in the sampling analysis[30]. For the trial, the ICT waste was fed into the recycling process, which represents standard pre-processing technology (see figure 3.1). It was not possible to achieve the exact distribution of categories, but the overall difference between the sampling results and the distribution

[30] At the planning stage of the trial, it was assumed that the amount and type of substances fed to the process can be roughly estimated by consulting literature data and data from dismantling trials (see appendix B and appendix C). This, however, required undamaged and complete products to be used as feed material, as bill of materials (BOMs) typically show the quantity of each material for a complete product. Since much of the equipment sampled and categorized in the sampling analysis was incomplete or damaged (see subsection 3.1.2), the samples could not be used for the recycling trial. Instead the recycler collected the trial feed in order to use (mostly) complete products.

of product categories in the trial feed material is marginal. Table 3.5 shows the number of products per category and the total weight of each category[31]. The overall weight of the feed material represented the minimum throughput necessary for steady-state operating condition of the shredding and sorting machinery.

Category No.	Category	Units	Weight (kg)	Uncertainty (±kg)	Weight (%)	Comment
1	PC monitor (CRT)	837	12,080	57.7	40.3	One cable per unit
2	Flat panel display (FPD)	158	703	7.0	2.3	Without cable
3	Desktop PC/server	895	8,564	85.6	28.6	One cable per unit, 15% without HD, 10% empty
4	Laptop/notebook/netbook	85	222	2.2	0.7	25% without HD, all without battery
5	Printer/fax/scanner/multifunctional	1,061	6,668	66.7	22.3	25% with cable, 75% without cable
6	IT misc.	225	69	0.7	0.2	
7	IT accessory	1,943	1,555	15.5	5.2	90% computer keyboard, 10% computer mouse
8	Mobile phone	112	10	<0.1	<0.1	Without battery
9	Phones (other)	110	87	0.9	0.3	Stations plus handsets plus 10.5 kg cable
	TOTAL		**29,958**	**806.1**	**100.0**	

Table 3.5: Trail Feed Material

3.2.1 Recycling Process Description

3.2.1.1 Pre-Processing

Prior to the trial, the facility, including shredders, sorting machines, conveyor belts, containers, grounds and storage bays were cleaned of all materials from previous operations. A general flowchart of the recycling process is shown in figure 3.1. The standard process at the recycling facility includes depollution, followed by shredding and a number of separation processes to sort the scrap into different output fractions. The depollution step involved removal of batteries from cell phones and laptops, as well as the removal of large ink cartridges from printing equipment. This step was carried out prior to the trial, i.e. the feed material as listed in table 3.5 (29,958 kg) represents depolluted ICT waste.

(1) in figure 3.1: As a first step of the trial, all CRT monitors were disassembled and separated into glass, plastics and metal scrap.

(2) in figure 3.1: The metal scrap from the CRT scrap (mostly cables, copper coils, PCBs, also some glass and plastics) was then sent to a shredder where it was fed, along with the rest of the trial feed material (categories 2 - 8). The shredder output was then processed over a magnet to separate out the ferrous and non-ferrous metals. In a subsequent step, aluminum was recovered from the non-ferrous scrap using an eddy current separator. The remaining non-ferrous material was processed over a sieve to separate very fine particles. Coarse scrap was run over another magnet to recover material that was referred to as 'magnetic fraction' by the operator of the facility. This fraction predominantly consisted of PCBs and metals, but also contained about 30% of plastics. What remains was reported

[31] The number of units in category 4 was small enough to check the products for completeness. 25% of the units were found to miss the hard drive (HD). The amount of products in category 3 was too large to check every unit for completeness, so it was estimated that 25% of the PCs were missing the HD as well.

as 'non-magnetic fraction', which consisted of plastics, some PCBs and glass. This 'non-magnetic fraction' was then processed over a series of optical and density based automated sorting steps to further recover PCBs and copper.

(3) in figure 3.1: In a final step, these PBCs and copper, along with the 'magnetic fraction' and the fines were shredded in a smaller shredder to produce an output fraction that is rich in copper and PM.

(4) in figure 3.1: The eddy current separator does not separate PCBs very effectively; hence the aluminum output fraction was processed over another separation step to recover PCBs. This separation step is part of the standard process at the facility but could not be physically be performed in this study. As a result, this process step was modeled (see table 3.6).

Overall, the technology at the recycling facility is estimated to represent standard mechanical pre-processing technology to recover secondary raw materials from WEEE. Research conducted prior to the trial showed that the combination and sequence of process steps varies slightly in different facilities, but the general approach of manual depollution, shredding and automated (magnetic, eddy current, density and optical) separation is widely applied in the WEEE recycling industry [104].

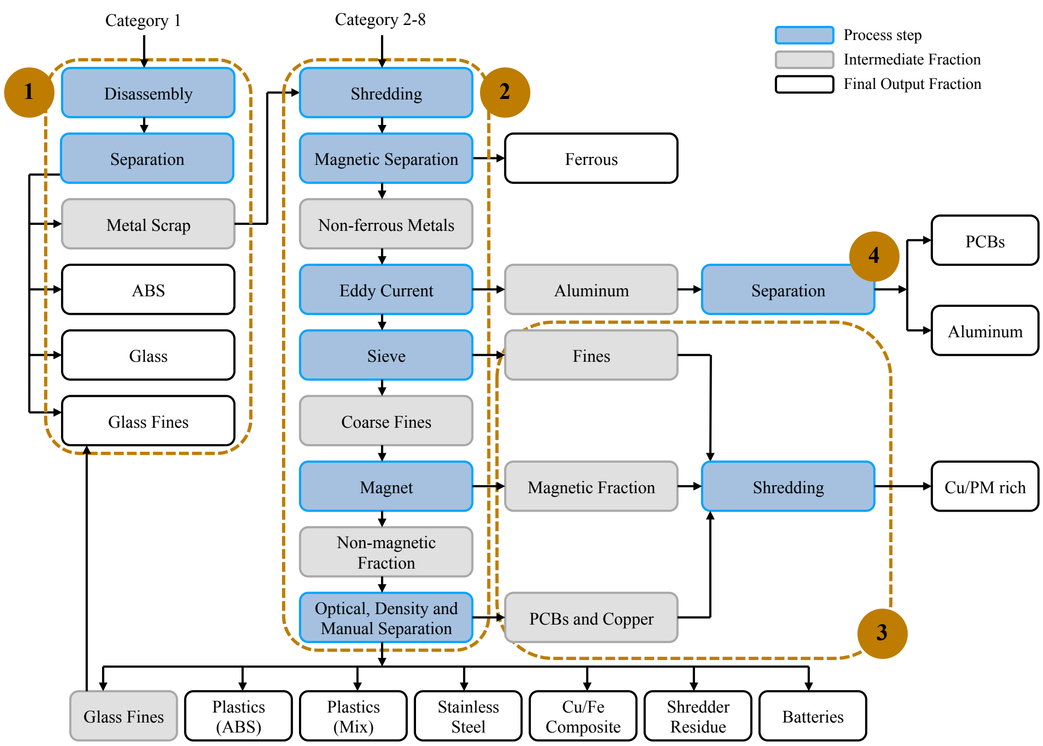


Figure 3.1: Simplified Flowchart of the Recycling Process (Pre-processing)

3.2.1.2 End-Processing

The output streams of the pre-processing facility are sold to a number of downstream recycling operations, where the material undergoes end-processing. Most end-processing facilities produce secondary raw materials (e.g. copper smelter, aluminum smelter) from the output fractions, while some output fractions do not qualify for secondary materials production and are incinerated (e.g. shredder residue). There exist several hundred pre-processing facilities in Europe (manual and mechanical treatment), but there are only a few metallurgical plants that are able to re-melt and refine scrap to produce secondary raw materials [140]. The end-processing steps of the trial feed material were modeled based on the material recycling rates of smelting and refining processes, which were obtained from literature references. Because this study puts specific focus on the secondary production of steel, aluminum, copper, gold, silver and palladium, the end-processing routes for these materials are explained in detail. For some other output fractions the end-processing route is briefly explained in subsection 3.2.4.

End-processing of 'PCBs from aluminum' output fraction and copper/PM rich output fraction: PCBs and other copper/PM rich output streams of WEEE pre-processing facilities in Europe are typically processed at integrated non-ferrous metals smelting and refining operations [70, 71, 171]. These type of operations involve pyrometallurgical and hydrometallurgical process steps and are able to recover and refine copper, gold, silver and palladium, as well as a number of other substances (e.g. lead, nickel) at different yields from the feed material [37]. Because the downstream end-processing facility of the pre-processing operation in this study is a copper smelter, the process yields used for the modeling of the end-processing of the 'PCBs from aluminum' and the copper/PM rich output fraction correspond to copper smelting operations [77]. The average recovery rate is estimated to be 95% for copper, 97% for silver, 98% for gold and 98% palladium. These values are published in the study of [77] and are based on empirical data and expert interviews [81]. A full list of average recoveries of metals at a copper smelter can be seen in appendix E.

There are different copper/PM smelting and refining operations; hence the following description is only a brief overview of the process. Prior to metallurgy, the feed material is sampled and crushed (if necessary) according to the requirements of the process [70]. The scrap is fed to a smelter (e.g. blast furnace) to concentrate copper and PM and segregate lead/lead slags. The smelter output is then processed in a converter and an anode casting plant, where copper anodes are produced. The copper anodes are then fed to a refinery, which produces secondary copper, as well as a precious metal containing anode slime. The anode slime undergoes further hydrometallurgical or pyrometallurgical treatment (depending on the operation) to recover and refine PM [33]. Ferrous metals and aluminum cannot be recovered in this process and are transferred into the slag [37].

End-processing of ferrous output fraction: The two main steel producing routes are electric arc furnace (EAF) and basic oxygen furnace (BOF) production, which both use ferrous scrap as feedstock. The production of 1 t of primary steel requires about 250 - 350 kg of steel scrap to control the temperature in the BOF [185]. The EAF processing route treats steel scrap exclusively to produce secondary steel [192].
The ferrous scrap output fraction from the pre-processing trial is a mix of low-alloyed steel and some iron[32]. The output fraction is sold to a ferro smelter operation, which uses EAF technology to produce secondary steel. The scrap is pre-heated and then smelted in the EAF. Oxygen is injected to the furnace to support the melting process. After the slags are separated from the molten steel, the steel is treated in a ladle furnace (addition of micro-alloys and ferro alloys) to adjust the temperature of the liquid steel for the casting operation. In a final step, the secondary steel is casted [51]. Secondary steel from EAF production is able to replace primary steel from BOF production [192], unless there are specific requirements regarding low residual element concentration for a steel product. The recovery rate of the EAF processing route varies between 81% to 96%, i.e. 1039 - 1231 kg of scrap are fed to the EAF to produce 1 t of secondary steel [51, 192]. For this analysis, a mean recovery rate of 89% was assumed.

End-processing of aluminum output fraction: Secondary aluminum is produced from two types of scrap, post-industrial scrap and post-consumer waste, at secondary aluminum refining operations [33]. Recycling of aluminum scrap can be done without any loss of quality and properties of the material. However, the presence of alloying elements (e.g. copper, magnesium, zinc, ferrous), i.e. the mix of different types of alloys in aluminum scrap from post-consumer waste makes the recycling process more complex and energy intensive than the recycling of post-industrial aluminum scrap. Mixed post-consumer scrap, such as the aluminum output fraction from the pre-processing trial is referred to as low-quality scrap by aluminum recycling operations [49].
The scrap is sorted and prepared (e.g. crushed, recovery of iron and other material, drying) before it is being fed to the furnace. The scrap is then processed in a furnace. It is then refined (alloying) and casted. Mixed shredder scrap (such as WEEE scrap) typically produces cast alloys, which can be used for the production of e.g. automotive and engineering components [86]. The recovery rate of the rotary furnace/refining/casting process is estimated to be 50% to 90% assuming low-quality scrap input [17]. For this analysis, it was estimated that 60% of the mass of scrap fed to the aluminum smelting process is recovered as secondary aluminum[33].

[32] High-alloyed steel, such as stainless steel, is less common in WEEE than low-alloyed and is party hand picked during pre-processing due to the economic value of stainless steel [140].
[33] The estimation of potential recovery rates for aluminum is likely to be an idealized description as the aluminum smelting/refining process. The production of secondary aluminum does not only depend on the amount of aluminum fed to the process, but more importantly on the amount of alloying elements in the scrap. Hence, the amount of aluminum fed to the aluminum smelting process does not automatically increase the secondary raw material yield.

3.2.2 Data Assessment Methodology

The following section explains the different steps of the experiment, which were necessary to assess the actual mass of secondary aluminum, copper, steel, gold, silver and palladium recovered from the trial feed material. The methodology to calculate the potential material yields and identify material losses is explained in subsubsection 3.2.2.2.

3.2.2.1 Assessment of Actual Secondary Raw Material Yields

The data collection approach for this part of the analysis includes five steps: weightings of trial feed material and output fractions, sampling of three output streams, modeling of the aluminum separation step, assaying (including data interpretation), modeling of the end-processing (including data interpretation). Figure 3.2 gives an overview over this part of the analysis.

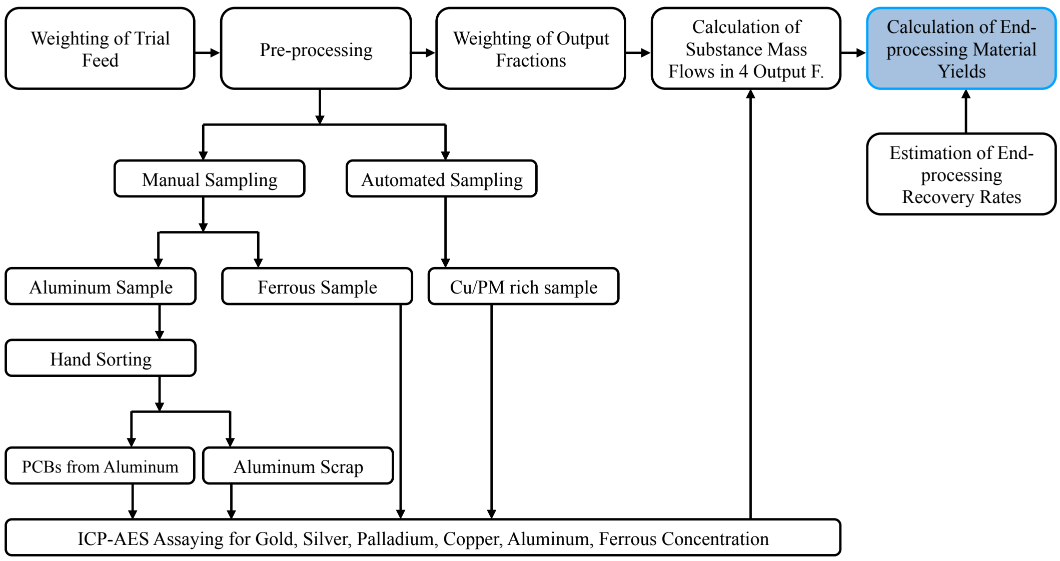


Figure 3.2: Methodology to Assess the Actual Mass of Secondary Aluminum, Copper, Steel, Gold, Silver and Palladium Recovered from the Trial Feed Material

(a) Weightings: The feed material was stored by category in containers, which were each weighed separately. The weight of each category was recorded and then consolidated to assess the overall weight of all categories. In order to double-check the weight, the feed material was put into trucks and driven over a truck scale prior to the trial. After each step of pre-processing, the output fractions were weighed separately. Weightings were conducted after the CRT shredding and separation process (1 in figure 3.1), after the shredding and magnetic separation/eddy current/sieve separation process, after the optical/density based separation process (2 in figure 3.1), and after the final shredding of copper/PM rich material (3 in figure 3.1). The weights of all final output fractions were consolidated and the total weight of the feed material was compared against the total weight of the output fractions.

(b) Sampling: Samples from the copper/PM rich output stream, the aluminum and the ferrous output fraction were taken[34]. The fractions were identified as relevant in terms of PM, ferrous, aluminum and copper recovery and covered over 53% of the total mass of the output streams. The sample from the copper/PM rich output fraction was taken using an automated sampling installation. In this procedure, the sampling installation was mounted underneath the small shredder (see (3) in figure 3.1) at the discharge outlet. The sampling installation is a rotary chain that holds buckets at regular intervals. The buckets intercept the falling stream at regular intervals.

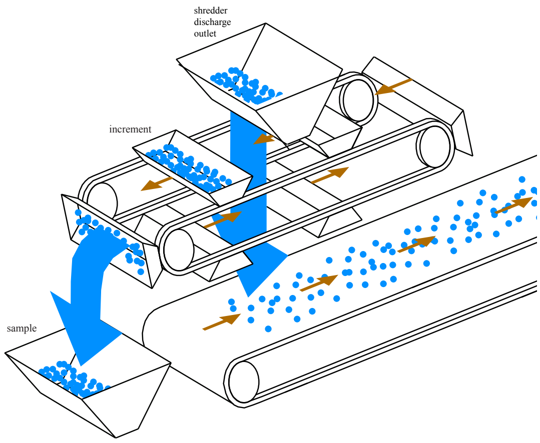


Figure 3.3: Simplified Layout of Automated Sampling Installation

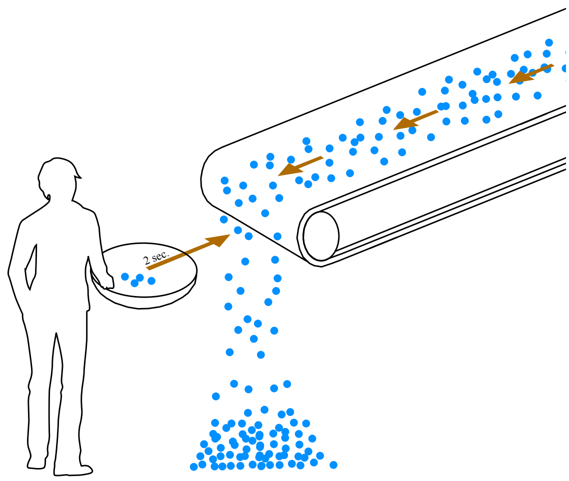


Figure 3.4: Simplified Layout of Manual Sampling Procedure

[34] For guidance on obtaining a representative sample the author refers to [99].

Figure 3.3 illustrates the automated sampling installation. More than 1200 increments were taken from the full cross-section along the entire stream in order to obtain a representative sample. Samples from the aluminum and the ferrous output fraction were taken manually as an automated sampling installation was not available. Samples were taken at regular intervals (ever 2 minutes) by momentarily positioning (approx. 2 sec.) a bucket at the discharge end of the conveyor belts and taking increments from the falling streams. 40 increments of each output fraction were taken. The total mass of the ferrous sample was 38.3 kg; the total mass of the aluminum sample was 18.4 kg. Figure 3.4 illustrates the manual sampling procedure. Both sampling procedures yield representative samples of the output streams, while samples that were taken manually are allocated higher uncertainties because less increments were taken (see subsection 3.2.3).

(c) Modeling of aluminum separation step: The aluminum separation step (4 in figure 3.1) is a standard part of the process in the facility that was evaluated, but was only modeled for this study. According to the operator of the facility, 90% of the PBCs contained in the aluminum output stream are recovered in this separation step. An estimated 10% of PCBs remain with the aluminum scrap. To model this process step, the aluminum sample obtained in (b) was hand sorted into PCBs and aluminum scrap. The PCBs, as well as the aluminum scrap were weighed. The total mass of PCBs and the total mass of aluminum scrap in the aluminum output fraction were calculated based on the share of both types of scrap in the sample. The mass of the PCBs that are recovered from the aluminum output fraction and the mass of the remaining aluminum scrap (including some PCBs) were calculated based on the estimated recovery rates for PCBs mentioned above. Table 3.6 gives an overview of the methodology to assess the amount of PCBs recovered in this separation step.

No.	Modelling Step
1	Hand sorting of sample taken from aluminum output stream into PCBs (18%) and aluminum scrap (82%)
2	Calculation of total mass of PCBs in aluminum output stream (136 kg)
3	Calculation of mass of PCBs that is recovered in the aluminum separation step, based on an estimated recovery rate of 90% (123 kg)
4	Calculation of mass of remaining aluminum scrap (including 10% of PCBs) (635 kg)

Table 3.6: Overview of Steps Necessary to Model the Final Separation of Aluminum

(d) Assaying (including data interpretation): Four samples (ferrous sample, aluminum scrap sample, 'PCBs from aluminum' sample, copper/PM rich output fraction sample) were sent to a laboratory for gold, silver, palladium, copper, ferrous and aluminum assay using inductively coupled plasma atomic emission spectrometry (ICP-AES)[35]. The substance concentration is expressed in parts per million (ppm) and percent (%). To calculate the total mass flow of a substance in an output fraction, the concentration identified in the sample is extrapolated to the total mass flow of the output fraction:

[35] The ICP-AES method is further explained in [112].

$$M^{s,f} = m^{s,f} M^f \tag{3.4}$$

where s is a specific substance
f is a specific output fraction
M is the absolute mass flow
m is the concentration expressed in ppm or %

The mass of gold, silver, palladium and copper in the copper/PM rich output fraction and in the PCBs are the basis for calculating the actual mass of secondary gold, silver, palladium and copper recovered from the trial feed material. Furthermore, the assaying results are required to determine the potential raw material yields of pre-processing (see subsubsection 3.2.2.2).

(f) Secondary raw materials recovered (including data interpretation): The end-processing of aluminum scrap, 'PCBs from aluminum', ferrous materials and copper/PM scrap was modeled based on end-processing recycling rates (k) obtained from literature references [51, 77, 192]. Table 3.7 shows the k values that were used for the calculations.

$$M^s_{out} = k^s M^s_{in} \tag{3.5}$$

where M_{in} is the mass of a material fed to the metallurgical process
M_{out} is the mass of secondary raw material recovered from the process
k is the recovery rate of the process
s is a substance/material

The mass of the ferrous fraction fed into the steel recycling process was obtained in step (a), the mass of the aluminum fraction fed to the aluminum recycling process was calculated in step (c) and the amount of copper, gold, silver and palladium present in the PCBs and the copper/PM rich fraction was obtained in step (d).

Source	**[77]**	**[77]**	**[192]**	**[51]**
Material	**Cu/PM rich**	**PCBs**	**Aluminum**	**Ferrous**
Gold	98%	98%	0%	0%
Silver	97%	97%	0%	0%
Palladium	98%	98%	0%	0%
Copper	95%	95%	0%	0%
Aluminum	0%	0%	60%	0%
Steel	0%	0%	0%	89%

Table 3.7: Estimated Recovery Rate of End-processing (k)

3.2.2.2 Assessment of Potential Secondary Raw Material Yields

The previous part of this chapter has outlined the methodology that was used to assess the amount of secondary gold, silver, palladium, copper, aluminum and steel that were actually recovered from 30 t of mixed ICT waste. The results are defined as the **Actual Raw Material Yields**. The following part of this chapter will describe how to determine the amount of material that could potentially have been recovered. The **Potential Raw Material Yield** is calculated based on the total amount of a substance present in the four output streams that were assayed (pre-processing) and the estimated yield of end-processing. The assessment of potential raw material yields is to be considered as a scenario analysis (What if all substances were perfectly separated in pre-processing?). The goal of this analysis is to compare the actual and potential raw material yield for six substances. Finally, the actual and potential yields will be evaluated with the AEB metric.

The methodology for the assessment of potential secondary raw material yields consists of five steps: calculation of total mass flow of ferrous, aluminum, copper, silver, gold and palladium in four output fractions, calculation of 'best-case recovery rate' of pre-processing, estimation of secondary gold, silver, palladium and copper potentially recovered.

(a) Calculation of total mass flow in four output fractions (potential yield): Based on the first law of thermodynamics, substances contained in the feed material can never dissolve within the process, but can be present in multiple output streams of pre-processing. All six materials of interest were detected in each one of the four output fractions, which were assayed. The total mass flow of a substance represents the sum of the mass flow in the ferrous fraction, the aluminum fraction, the 'PCB from aluminum' fraction and the copper/PM rich fraction. This can be expressed as follows:

$$M^{s}_{potential} = \sum_{f=1}^{n} m^{s,f} M^{f} \tag{3.6}$$

It is important to note that the total mass flow assessed in this step does not represent the total mass flow of copper, silver, gold and palladium in the trial because only four output fractions were assayed. For a detailed explanation, see subsubsection 3.2.2.2 step (b).

(b) Calculation of 'best-case recovery rate' of pre-processing: The actual recovered mass (M^{s}_{actual}) of copper, gold, silver and palladium is the amount of these substances present in the copper/PM rich output fraction and in the 'PCBs from aluminum'. The actual recovered mass of ferrous equals the amount of ferrous present in the ferrous fraction and the actual recovered mass of aluminum represents the amount of aluminum present in the aluminum scrap fraction.

This is based on the fact that PM and copper are only recovered from the copper/PM rich output fraction and the 'PCBs from aluminum', ferrous is only recovered from the ferrous fraction and aluminum only from the aluminum fraction. For example, any content of ferrous in the 'PCBs from aluminum' is not available for raw material recovery, because the end-processing of PCBs does not recover ferrous material.
The 'best-case recovery rate' of a substance describes the proportion of the total mass flow $M^s_{potential}$ to the actual recovered mass M^s_{actual}.

$$RR(s) = \frac{M^s_{actual}}{M^s_{potential}} \times 100 \tag{3.7}$$

where RR is the 'best case recovery rate' of a substance
$M_{potential}$ is the total mass flow or the mass that is potentially recoverable
M_{actual} is the actual recovered mass

It is important to note that the recovery rate shown here does not represent the overall recovery rate of the recycling process and does not compare to the term 'recycling rate' discussed in e.g. [64, 180, 181]. This is because there is no information available on the potential presence of gold, silver, palladium, ferrous, aluminum, and copper in shredder output fractions that were not assayed (e.g. plastics, glass). The total mass of the output fractions for which an assay was available covers 53% of the total mass of all shredder output fractions. In case the remaining 47% of the output mass did not contain any PM, ferrous, aluminum, or copper, the values calculated through Equation 3.7 could be considered as the total recycling rate of the process. However, samples of some output fractions were manually separated and contained pieces of metal and PCB, which supports the assumption that the recovery rate shown here does not qualify to describe the total efficiency of the process. The recovery rate shown here can thus rather be described as a 'best case recovery rate'.

(c) Estimation of secondary raw materials potentially recovered: Based on their total mass flow $M^s_{potential}$, the end-processing step can be modeled. This is a theoretical scenario showing the amount of secondary raw materials which could be recovered if $M^s_{potential}$ ended up in a recycling process that qualifies for recovery of substance s. Hence, it is assumed that there are no losses of copper, silver, gold and palladium in the ferrous and the aluminum fraction, no losses of aluminum in the ferrous fraction, the copper/PM rich material and the PCBs, and no losses of ferrous in any of the 'non-ferrous' fractions. The yields of the end-processing step can be calculated on the basis of Equation 3.5 and the estimated recycling rates shown in table 3.7.

3.2.3 Uncertainty

Uncertainties in the data are a due to three types of errors that can occur during the recycling trial: weighting errors, sampling errors and assaying errors (see subsubsection 3.2.2.1) [31]. Weighting errors are fixed to the scales that are used to obtain the weight of the feed material and the output fractions. Four scales were used in the trial, a large floor scale to weigh the output fractions and some of the larger input categories ($\pm 1\,kg$) and a small floor scale to weigh the input categories ($\pm 0.5\,kg$). For some larger input categories and output fractions several weightings were necessary, which increases the uncertainty. The CRTs were weighted on a truck scale ($\pm 20\,kg$) and the mobile phones were weighted on a digital scale with an uncertainty of < 100 g.
The uncertainties from sampling and assaying outweigh the uncertainties from weighing. Thus, all input categories and output fractions (except for the CRT input and the mobile phones input) were allocated a weighing margin of error of 1%, which is a conservative estimate for the majority of categories and fractions. In the sampling step, an uncertainty is allocated due to the heterogeneous mix of the material. According to the operator of the recycling facility, the uncertainty for manual sampling is estimated to be 10% and the uncertainty for automated sampling is estimated to be 5%. This is because the automated sampling installation is able to obtain a very large number of increments at fixed intervals. The uncertainty of the ICP-AES assaying results is estimated to be 2% [31]. The uncertainties of weighting, sampling and assaying are independent from each other and can be combined into the total error by applying the Gaussian error propagation law [23, 27]:

$$\Delta A_{total} = \sqrt{(\Delta A_{Weigthing})^2 + (\Delta A_{Sampling})^2 + (\Delta A_{Assaying})^2} \tag{3.8}$$

where ΔA_{total} is the uncertainty of the total mass flow

The uncertainty of the total mass flow ΔA_{total} is allocated to the mass flow of a substance in an output fraction $M^{s,f}$. The Gaussian law also applies to the calculation of the uncertainty allocated to the total mass flow $M^{s}_{potential}$.

3.2.4 Results

Output fractions of pre-processing: The weights of the output fractions, which were produced in the trial are shown in figure 3.5. The 'glass' output fraction almost exclusively originated from CRT monitors, as well as the ABS plastics, which was baled (compacted) right after the CRT shredding processes and sent to a plastics recycling plant. More ABS was recovered from the 'non-magnetic fraction' because it can be sold at a higher price than 'plastics mixed'. The ferrous/copper composite is material that is hand picked at different stages of the sorting process and mainly consists of motors and coils.

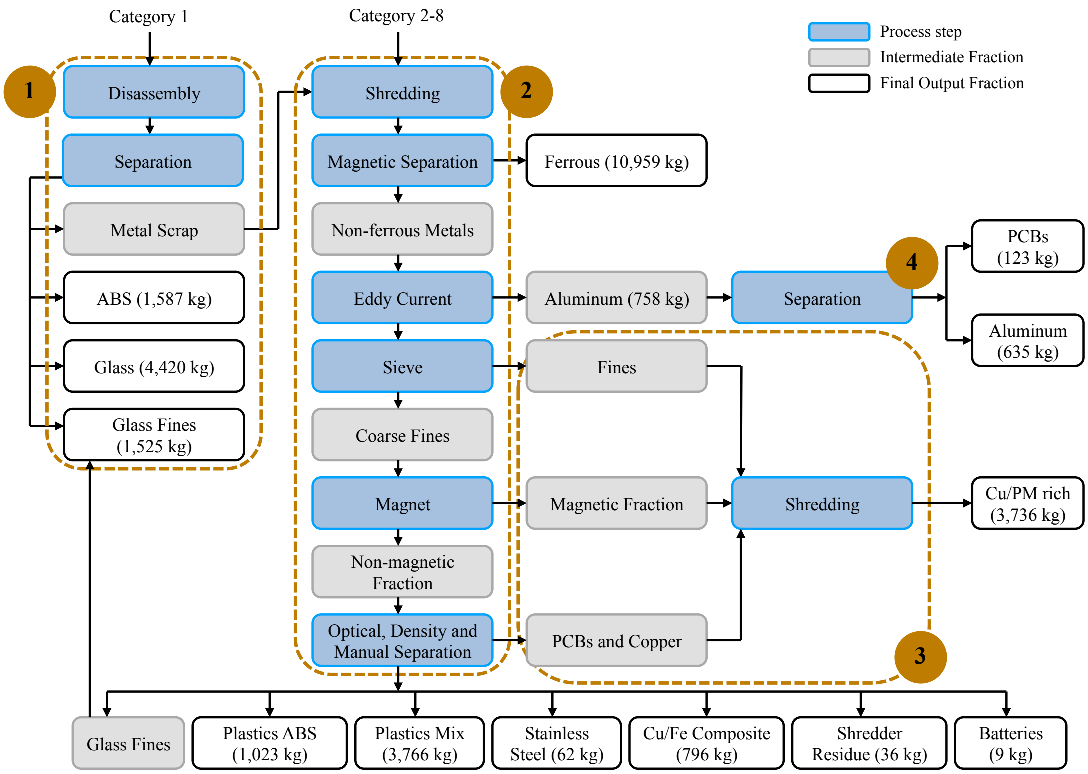


Figure 3.5: Weight of Output Fractions from the Pre-processing Trial

The components are recovered because they would otherwise be discharged into the ferrous output but are more valuable than ferrous scrap due to their 40% copper content. Stainless steel is also recovered by hand picking for economic reasons. This material would otherwise flow into the aluminum fraction. Although representing less than 0.1% of the total output, the origin of the batteries is unclear but it is likely that some batteries were missed out in the depollution step. The 'shredder residue' mainly consisted of foils, rubber and Styrofoam, and is sent to incineration for energy recovery. The total mass of the output differs to the total mass of the feed material by 4%. According to the operator of the recycling facility, the difference between the input and the output weight can be up to 5% so the difference here is not abnormally high, but lies along the upper limit of an acceptable difference[36].

Analytical Results of Four Output Fractions: The ICP-AES assay results presented in table 3.8 are informative with respect to some of the substance flows in the output fractions of the pre-processing facility[37]. The uncertainty of the assaying results (concentration

[36] The difference can be due to a number of reasons, for example if shredder output was inadvertently dumped into a wrong container before a weight was obtained. The trial was monitored at all times and the staff was well instructed prior to the trial but inaccuracies are not avoidable with the size of the facility and the amount of material handled. The difference can partly also be related to weighing uncertainties.

[37] The concentration of ferrous in the ferrous fraction, and the concentration of aluminum in the aluminum fraction were estimated based on interviews with the laboratory that was subcontracted for the assay.

in ppm or %) is ±5.4% for the copper/PM rich fraction and ±10.2% for the other output fractions, and covers the uncertainty of weighing, sampling and assaying. Table 3.8 shows the results of the assaying, including the absolute uncertainty of each value ($\pm g/kg$).

Output Fraction	Weight (kg)	Gold			Silver			Palladium		
	±1%	ppm	g	± g	ppm	g	± g	ppm	g	± g
Cu/PM rich material	3,736	29.0	108.3	5.9	322.0	1,203.0	65.9	6.0	22.4	1.2
Ferrous	10,959	6.9	75.6	7.7	102.0	1,117.8	114.5	2.6	28.5	2.9
Aluminum	635	23.0	14.6	1.5	155.8	98.9	10.1	2.8	1.8	0.2
PCBs from Aluminum	123	128.0	15.7	1.6	329.0	40.5	4.1	12.0	1.5	0.2
TOTAL			**214.3**	**39.8**		**2,460.2**	**457.0**		**54.2**	**10.1**

Output Fraction	Copper			Aluminum			Ferrous		
	%	kg	± kg	%	kg	± kg	%	kg	± kg
Cu/PM rich material	20.5	765.9	41.9	2.8	104.6	5.7	4.7	175.6	9.6
Ferrous	6.2	683.8	70.1	5.6	608.2	62.3	85.0	9,315.2	954.5
Aluminum	3.9	24.5	2.5	83.7	531.8	54.5	3.7	23.4	2.4
PCBs from Aluminum	30.7	37.7	3.9	8.8	10.8	1.1	1.5	1.9	0.2
TOTAL		**1,511.9**	**280.8**		**1,255.5**	**233.2**		**9,516.0**	**1,767.5**

Table 3.8: Analytical Results of Four Trial Output Fractions (Substance Concentration and Absolute Mass)

As for the total mass flow, the results show that the mass flow of gold and silver in the ferrous fraction accounts for 35% (gold) and 45% (silver) of the total mass flow of these substances. For both substances, the mass flow in the ferrous fraction is almost as large as in the copper/PM rich fraction, which contains 51% of the gold and 48.9% of the silver. The mass of gold and silver in the PCBs is only 7.3% (gold) and 1.6% (silver) of the total mass flow. This demonstrates that the total mass flow of the output fraction is essential when looking at the substance concentrations. The concentration of 6.9 ppm of gold in the ferrous fraction appears reasonably low compared to 128 ppm detected in the PBCs, but the mass flow of a fraction is crucial for the absolute mass of a substance[38]. The mass of palladium in the ferrous fraction is even larger than in the copper/PM rich fraction.

Best-case Recovery Rates of Pre-processing: The distribution of substances across the output streams can be seen in figures 3.6 to 3.11. The blue edging in these figures indicates the output stream from which the substance can be recovered in the end-process and thus the best-case recovery rates of pre-processing. The best-case recovery rate is the lowest for aluminum and palladium, which are both recovered at a rate of $< 50\%$. In the case of aluminum, the largest mass flow is contained in the ferrous output fraction, from which aluminum is not recovered in end-processing.

[38] The relationship of mass flow and substance concentration is extensively discussed in [31]. For comparison, this study finds 27 ppm of gold, 329 ppm of silver and 5 ppm of palladium in the ferrous output fraction [30].

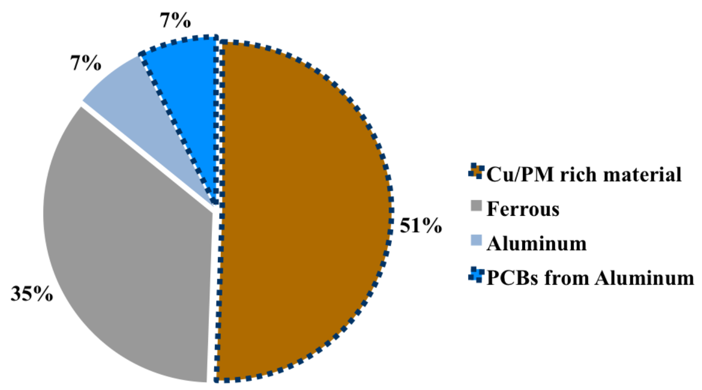


Figure 3.6: Gold, Best-case Recovery Rate of Pre-processing

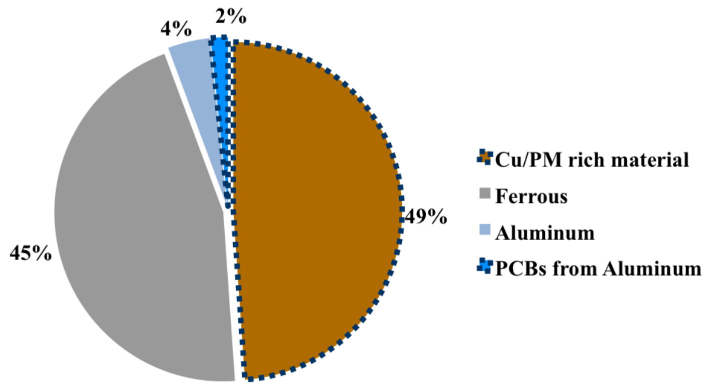


Figure 3.7: Silver, Best-case Recovery Rate of Pre-processing

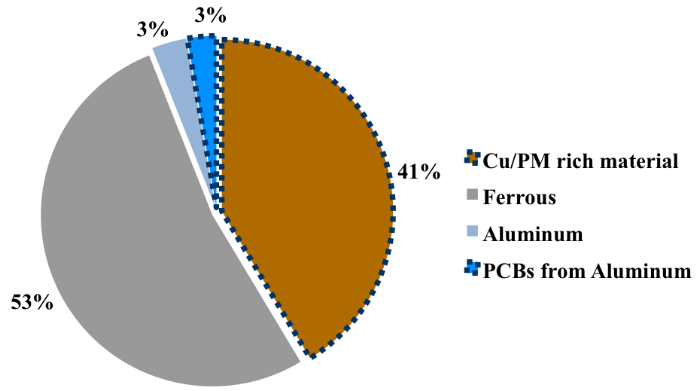


Figure 3.8: Palladium, Best-case Recovery Rate of Pre-processing

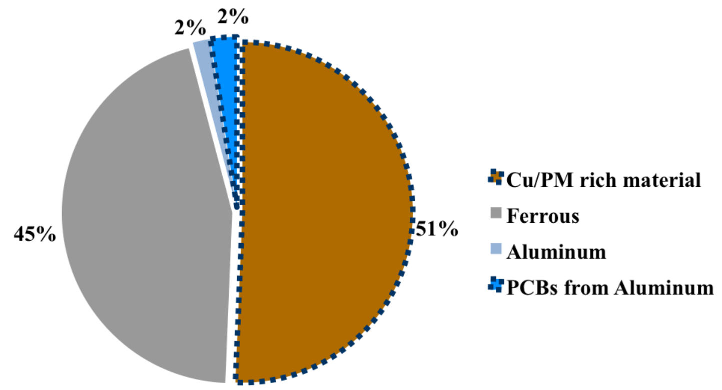


Figure 3.9: Copper, Best-case Recovery Rate of Pre-processing

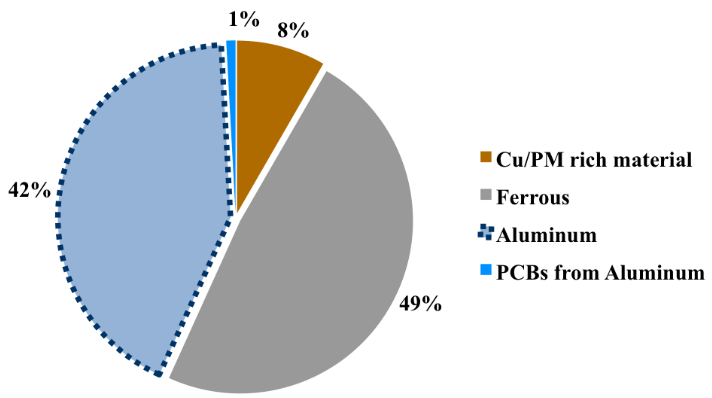


Figure 3.10: Aluminum, Best-case Recovery Rate of Pre-processing

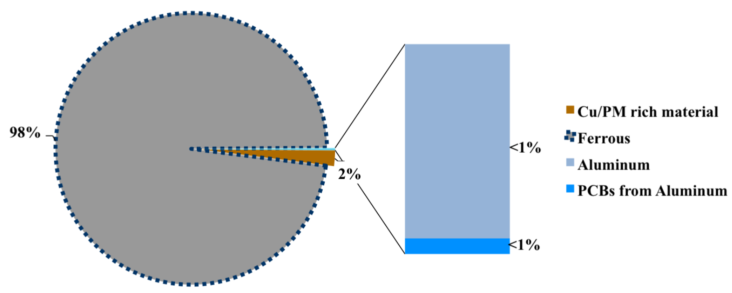


Figure 3.11: Ferrous, Best-case Recovery Rate of Pre-processing

Actual Secondary Raw Material Yields: For the end-processing, the output fractions are sent to the operations described in subsubsection 3.2.1.2. Based on the recovery rates of the copper smelter, EAF process and the aluminum smelter, the secondary raw material yields of the recycling trial can be calculated and are presented in table 3.9. The uncertainties of the values refer to the uncertainty of the pre-processing results. The end-processing recovery rates are based on literature references and their uncertainty cannot be quantified. The uncertainty of the PM and the copper recovery rates is estimated to be low because the recovery rates obtained from the study by [77] are consistent with the recovery rates documented in other references [24, 181].

Table 3.9 shows the estimated amount of secondary gold, silver, palladium, copper, aluminum and steel that were recovered from 30 t of mixed ICT waste in the trial.

Material	Cu/PM rich	PCBs	Aluminum	Ferrous	TOTAL
Gold (g)	106.2 ±5.3	15.4 ±1.6	0.0	0.0	**121.6 ±14.1**
Silver (g)	1,166.9 ±58.3	39.2 ±4.0	0.0	0.0	**1,206.1 ±140.1**
Palladium (g)	22.0 ±1.1	1.4 ±0.1	0.0	0.0	**23.4 ±2.7**
Copper (kg)	727.6 ±36.4	35.9 ±3.7	0.0	0.0	**763.4 ±88.7**
Aluminum (kg)	0.0	0.0	319.1 ±32.7	0.0	**319.1 ±32.7**
Steel (kg)	0.0	0.0	0.0	8,290.5 ±849.5	**8,290.5 ±849.5**

Table 3.9: Actual Secondary Raw Material Yields (Material Yield after End-processing)

Potential Secondary Raw Material Yields: Figure 3.12 illustrates the difference between the potential and the actual secondary material yields from the trial feed material.

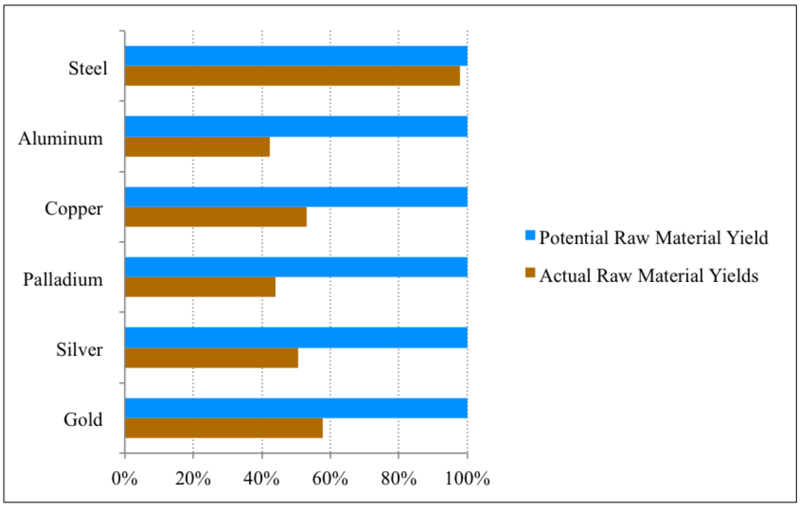


Figure 3.12: Comparison of Secondary Raw Materials Actually Recovered and Potentially Recoverable

These values that underly the potential yield in Figure 3.12 correspond to a scenario in which the total mass ($M^s_{potential}$) of each substance (see total values in Table 3.8) is steered to an end-processing facility, which is able to recover the substance for the production of secondary raw material. As a matter of fact, the ratio between 'mass actually recovered' and 'mass potentially recovered' corresponds to the best-case recovery rates $RR(x)$ of pre-processing. The potential yield is a theoretical scenario, but shows that the secondary raw material yield could be significantly increased if pre-processing separated substances more effectively.

3.3 Results Applied to AEB Metric

The AEB metric provides an effective tool to evaluate the differences between the actual and potential secondary raw material yields from an environmental viewpoint. To obtain values for the total AEB in each impact category, the mass of each material is multiplied with the respective AEB value shown in tables 2.3 to 2.7. The output of this interpretation is a total AEB value for each of the seven environmental impact categories demonstrated in figure 3.21.

$$AEB_c = \sum_{s=1}^{n} M^s_{actual/potential} AEB^s_c \tag{3.9}$$

where c is an environmental impact category

The results of the comparison of category AEBs for the actual trail yields and the potential yields are shown in figures 3.13 to 3.19.

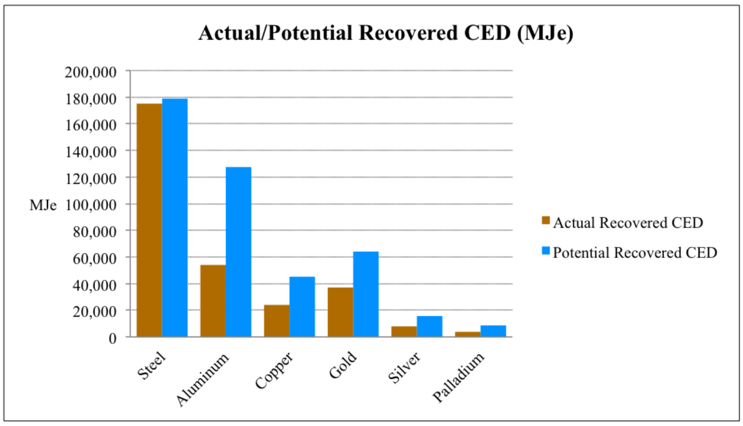


Figure 3.13: Actual and Potential Recovered CED (MJe)

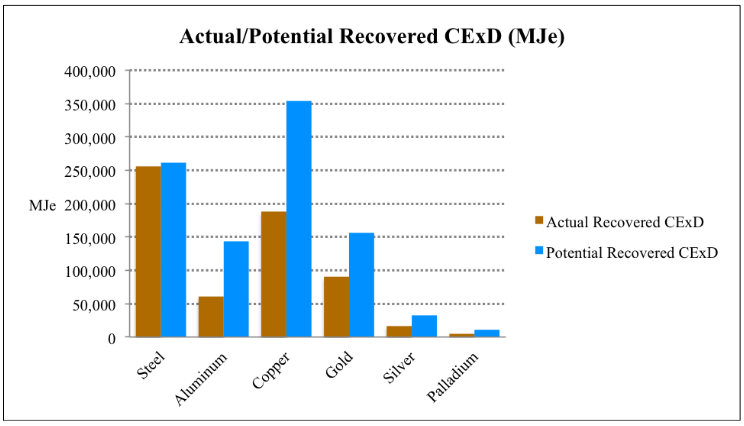


Figure 3.14: Actual and Potential Recovered CExD (MJe)

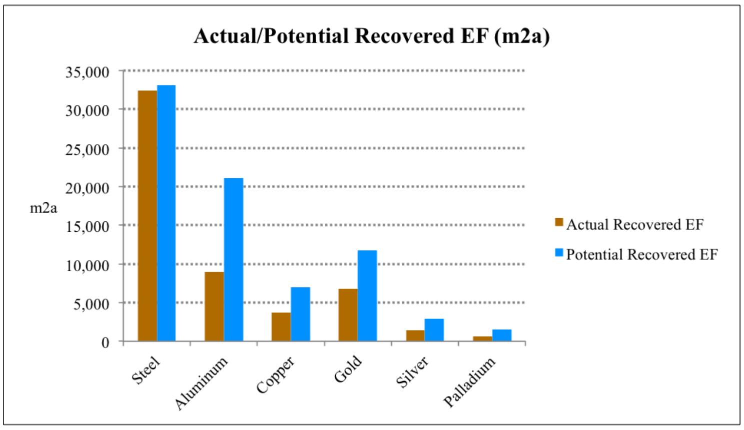


Figure 3.15: Actual and Potential Recovered EF (m^2a)

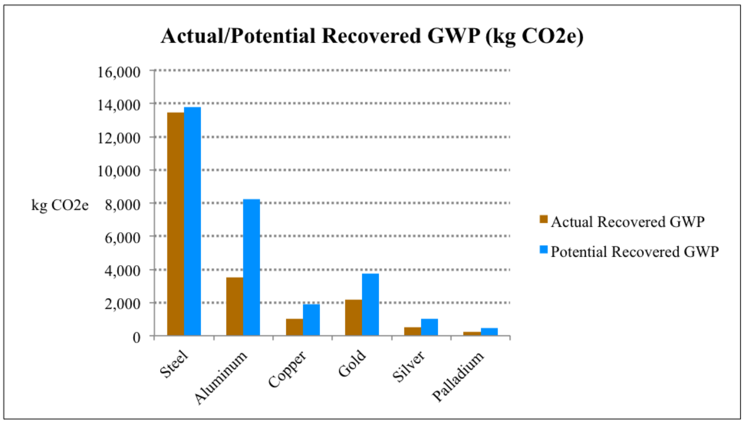


Figure 3.16: Actual and Potential Recovered GWP (kg CO_2e)

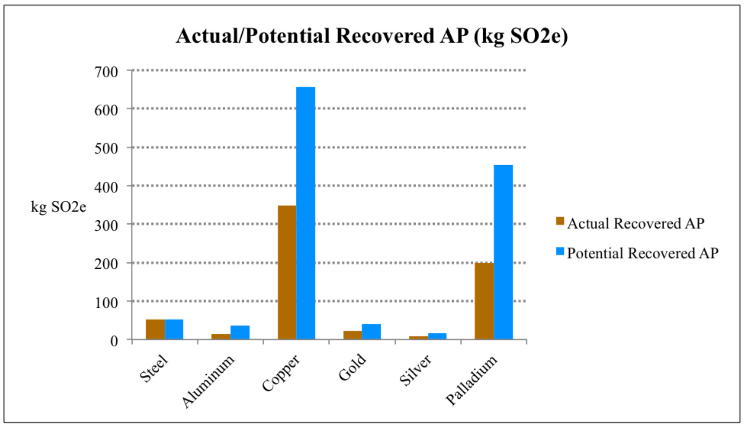


Figure 3.17: Actual and Potential Recovered AP (kg SO_2e)

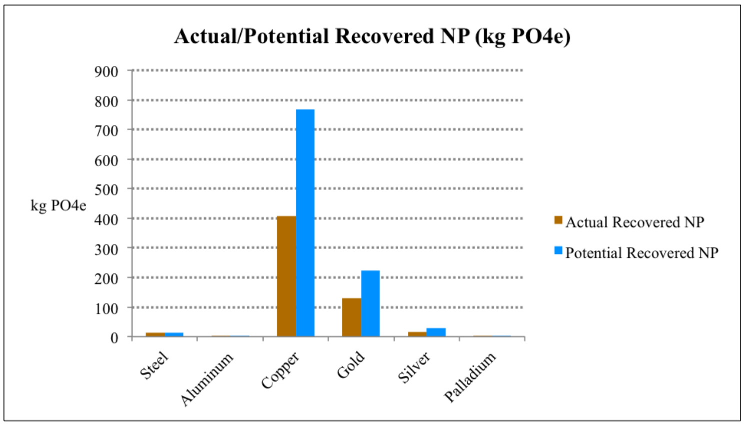


Figure 3.18: Actual and Potential Recovered NP (kg PO_2e)

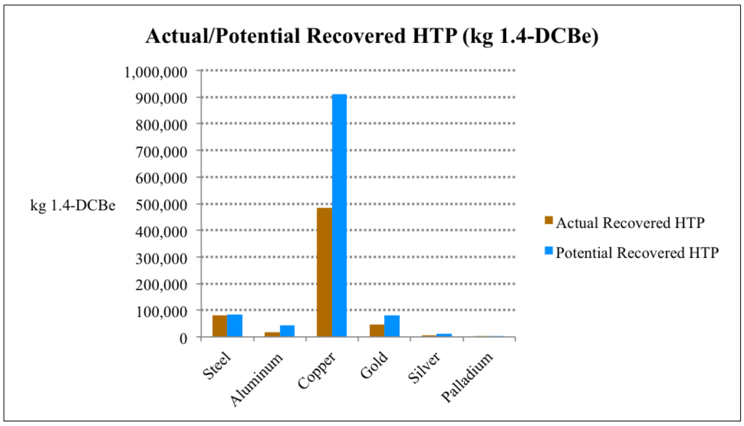


Figure 3.19: Actual and Potential Recovered HTP (kg $1.4 - DCBe$)

Regarding the actual AEB, steel accounts for the largest share of the total avoided burden in the CED, CExD, EF and GWP categories, and copper dominates in the CML 2001 impact categories. Despite their significant AEB per kg of material, gold, silver and palladium cover only a small share of the total actual AEB in all impact categories (with the exception of AP, which is dominated by palladium and copper). However, the AEB values are relatively high given the small mass flow of these materials. This confirms the recycling of PM is particularly effective from an environmental viewpoint (i.e. small amounts of recovered mass result in relatively large environmental benefits), which is illustrated in figure 3.20.

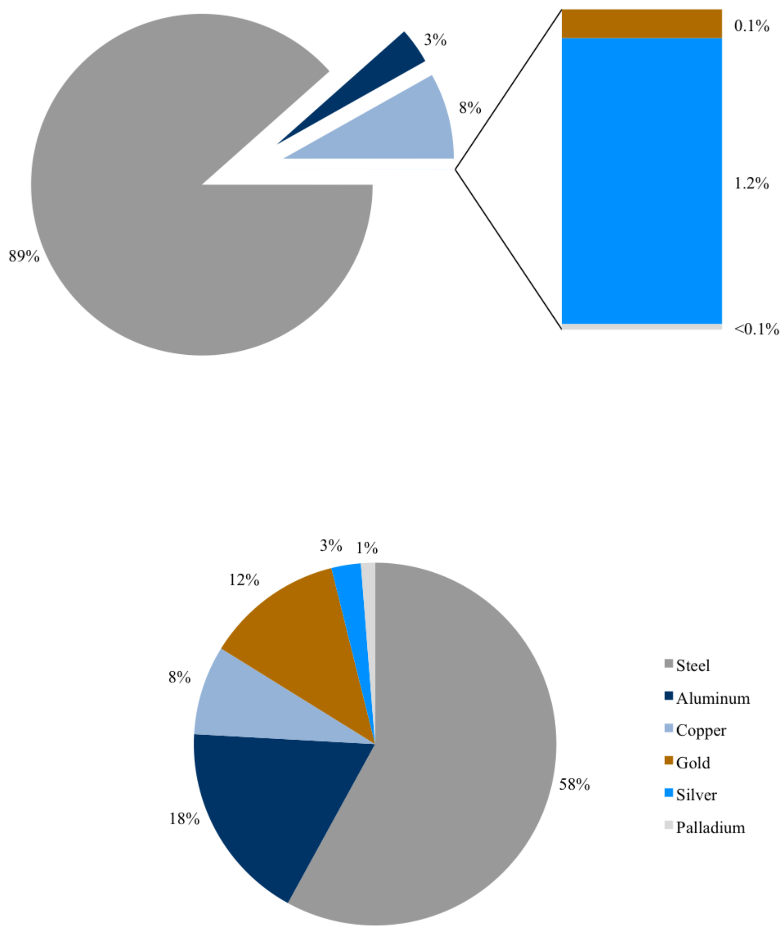


Figure 3.20: Comparison of Weight Share and Recovered CED Share (Gold)

The dominance of copper in the CML 2001 categories is illustrated in figure 3.21 and can be analyzed by consulting the 'per kg AEB' values shown in table 2.7. Out of the three metals accounting for a large mass flow in the trial (ferrous, aluminum, copper), copper shows much higher recovered AP/NP/HTP values than aluminum and ferrous (e.g. the recovered HTP of 1 kg of copper is 11 times larger than that of aluminum and 65 times larger than that of steel). The high values for copper in the AP impact category are mainly due to SO_2 (and to a smaller extent ammonia and nitrogen oxide) emissions in the primary copper production process. These types of emissions are neither generated in the copper recycling process, nor (or to a much lesser extent) in primary steel and aluminum production, so the potential to avoid these emissions is one of the benefits of secondary copper production. As for the NP category, the high values for copper are almost exclusively due to the emission of phosphates in primary copper production. The reason for high copper values in the HTP category is emissions of arsenic, and to a lesser extent nickel, cadmium and other emissions to air and water, which occur in primary copper production. Again, much less of these emissions occur in secondary copper production (so the difference between primary and secondary values is high), and also in primary steel and aluminum production. Overall, the prominent position of copper in the CML 2001 categories is a result of the mass flow of copper, combined with the high recovered AP, NP and HTP values per kg of copper (compared to the other mass-relevant materials steel and aluminum). The recovered AP/NP/HTP per kg of PM is certainly higher than that of copper, but the mass flow of these metals is comparably low.

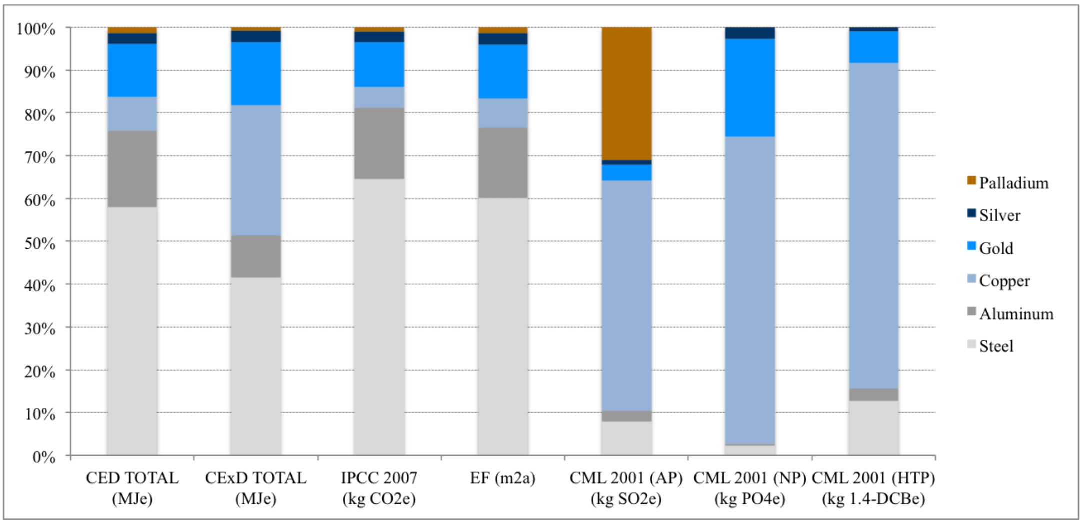


Figure 3.21: Overview of Material Share per Impact Category

Palladium shows large avoided impacts (compared to silver and gold) in the AP category because of extensive SO_2 emissions in the primary palladium production process.
When looking at opportunities to improve the AEB performance of the recycling trial, the largest potential across all categories is in improving the pre-processing recovery rates of copper, PM and aluminum. Steel shows little potential for improvement due to the high recovery rate in pre-processing. More effective separation of aluminum in the pre-processing trial would particularly lead to better overall performance in the CED, EF and GWP categories, whereas overall CExD, AP, NP and HTP performance would profit from higher yields of copper. The data for actual and potential performance in all categories can be found in appendix F. Table 3.10 shows the overall improvement potential of each impact category, as one compares the performance of the actual and potential trial yields.

Impact Category	**Potential to Improve Actual Performance**
CED TOTAL (MJe)	46%
CExD TOTAL (MJe)	55%
GWP (kg CO2e)	40%
EF (m2a)	43%
AP (CML 2001) (kg SO2e)	94%
NP (CML 2001) (kg PO4e)	83%
HTP (CML 2001) (kg 1.4-DCBe)	77%

Table 3.10: Improvement Potential of Actual Performance

3.4 Discussions

In the previous chapter a base case of ICT waste recycling was built to assess empirical data on the amount and type of raw materials currently recovered from WEEE. The results of this trial were used to demonstrate the effectiveness of the AEB methodology.
There are certainly opportunities to expand the empirical data collection, by including more substances and output streams into the analysis. For the purpose of this study, the material flows and end-processing yields of six substances were put in focus and four output streams were chemically assayed. Future studies could include additional materials, e.g. plastics and other base materials (lead, nickel) and the end-processing yields of more output streams, for example batteries and product units (such as the copper/ferrous composite in the trial). Such analysis is comprehensive, but would provide a complete picture of the total amount of raw materials extracted from WEEE today. In light of the discussions around criticality (see subsection 1.1.1), it would be worthwhile to engage in an analysis on the material flows of 'critical' substances contained in WEEE. These substances are presently not among the materials that are recovered from WEEE. However, the combination of an investigation into the flows of e.g. gallium, indium and rare earth

elements in pre-processing and the assessment of environmental impact data would be important to understand the opportunities of recycling critical substances.

This study has determined 'best-case recovery rates' for six materials, which is an efficient way to provide validation for the methodology. As a matter of fact 'best-case recovery rates' do not provide a complete picture on the substance losses that occurred in the trial. As a consequence of 'best-case recovery rates', the AEB improvement potential stated in table 3.10 is to be understood as the minimal potential to improve performance. To obtain the total recovery rates, the feed material would need to be characterized on a substance level. This data is difficult (if not impossible) to obtain because of the complex material composition of the mixed WEEE stream. As previously mentioned, the study of [31] developed a methodology to estimate the mass of some substances in the trial feed material, which requires chemical assaying of all output fractions. Because the aim of the trial described in section 3.2 is different from the research goals in [31], such extensive assaying does not seem reasonable in the context of this study. However, some analysis was undertaken to characterize the feed material based on literature data and data from extensive product dismantling trials by WEEE Analysis Service KERP[39]. The results of this analysis can be found in appendix C.

One of the basic assumptions of the recycling trial was that mechanical pre-processing and the combination of depollution/shredding/separation describes the status quo of WEEE recycling in Europe. Because the results of the trial are used to estimate the overall performance of OEMs in WEEE collection and recycling programs, the case is considered representative for the current situation of electronics recycling. Notwithstanding, it must be acknowledged that a large variety of different facilities and technologies exist to process EOL electronics [153]. Not all of these facilities use mechanical technology, many also use a manual approach to dismantle products and recover materials [158]. Some facilities also use mechanical dismantling technology [96]. Even amongst the large shredding facilities in Europe (such as the one portrayed in the previous chapter), some differences exist with respect to the level of dismantling prior to shredding, the recovery of certain units/material streams and the sorting technology. The case in this study adequately describes one possible and the most common way to process WEEE [96], but does not cover the multitude of approaches and technologies that currently exist.

3.5 Conclusions

The question remains as to how the rate at which aluminum, copper and PM were recovered in the trail could be improved in practice, in order to tap the full potential in terms of AEB performance. A logical strategy is to improve the separation of substances in pre-processing in order to better steer substances into adequate end-processing routes.

[39] The dismantling trials were carried out by KERP Research Elektronik und Umwelt GmbH, who provided datasets on the material composition of each product category present in the trial feed material.

In the case of this trial, none of the precious metals rich components of the feed material were manually removed prior to shredding, which may lead to lower PM/copper recovery rates. Even if the amount of PM in the feed material cannot be accurately quantified, it is certain that the largest amount of copper/PM in the trial feed came from the PCs (which contain large PCBs and covered a significant mass share of the trial feed) (see appendix B). Removing these PCBs from the PCs prior to shredding would be a first step to reach higher PM and copper recovery rates and improvement of AEB performance.

It was also shown that the indicators selected for the AEB methodology provide a diverse view on the environmental effectiveness of material recycling. While the impact of ferrous materials dominates in all single-score indicator categories and GWP, the CML 2001 categories unveil the AEB of copper recycling.

There is also a contrast between the material that accounts for the largest AEB (steel) and the materials that hold the largest potential for improvement of overall AEB performance (copper, PM and aluminum). This supports the argument that the recycling of materials with high mass streams must be maintained, while the recovery of materials with lower mass streams must be improved.

To conclude, the argument laid out in subsection 2.2.1 was that the performance of the AEB metric can be influenced by a number of variables in the recycling system. By combing the results of the recycling trial with the AEB values for six materials, table 3.10 in fact shows that the performance of the trial can be increased by 40% (GWP) to 94% (AP). Most importantly, this improvement is possible without increasing the mass of WEEE collected and sent to a recycling facility. The conclusion that OEMs should not only look at the increase of collected WEEE, but also turn their attention to the effectiveness of raw material recovery is perhaps the most important finding of the AEB methodology and the fundamental contrast to mass based corporate performance metrics.

4 Scenario Analysis

The main finding of the previous chapter is that the AEB of a recycling program can be increased by at least 40% if materials are recovered at a higher rate in pre-processing. In operational reality, AEB performance is also influenced by the mass of EOL equipment collected for recycling and the type of material collected and recycled (in knowing that each material shows different AEB values). The following chapter develops two modeled scenarios, which illustrate the influence of type of material collected and recycled (covering the substance variable i and the mass variable M_{in}) combined with the influence of process recovery rates (k in the recycling system) on AEB performance. The results of this exercise can be used to guide strategic development of WEEE collection and recycling programs.

4.1 Scenario in Context

The modeled cases developed in the following chapter exclusively focus on one type of WEEE, EOL mobile phones (as opposed to mixed ICT waste in the empirical case). The processing route is depollution followed by metallurgical processing in scenario 1, and depollution, mechanical pre-processing and metallurgical end-processing in scenario 2. The recycling process described in scenario 2 is thus identical to the recycling process illustrated in the mixed ICT waste case; only the process feed (input) is different. In an effort to understand how the AEB performance of a mobile phone collection program compares against the mixed ICT waste collection program, the recovery of secondary gold, silver, palladium, copper, aluminum and steel from mobile phones is investigated in both scenarios. Environmental data (AEB values of all impact categories defined in subsubsection 2.2.4.2) are used to evaluate the mass of secondary raw materials recovered in scenario 1 and 2. Figure 4.1 summarizes the system variables of the AEB methodology (input, recycling process, output and environmental impact assessment) and shows where data input in scenario 1 and 2 will be different from the mixed ICT waste case.
In recent discussions around resource efficiency and the development of closed loop economies, increasing focus has been put on the collection and recycling of EOL mobile phones [45, 95, 131, 145][40].

[40] In the context of sustainable production and consumption, the term 'closed loop' refers to the idea of a zero waste economy, in which all EOL materials can be reapplied in the production of new goods. The opposite is an 'open loop' economy, in which EOL goods and materials are e.g. dissipated or land-filled, without being used in a new application [22].

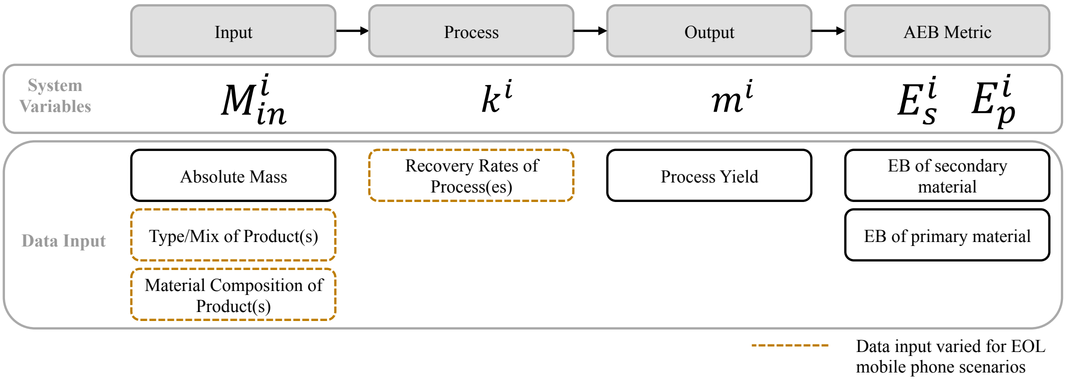


Figure 4.1: Overview of System Variables

Among the main reasons for this are:

(1) EOL mobile phones hold a number of valuable substances, e.g. PM and copper, which can be recycled, provided that the waste enters an appropriate recycling process. The total mass of PM per phone is low (compared to the mass of e.g. plastics and glass) [148] but the concentration is higher than in most other ICT products [127] and also higher than in virgin metal ores [11]. In addition to monetary value, the recovery of potentially critical substances, such as PGM, antimony and tellurium has recently brought mobile phone recycling to the attention of industry, media and legislators [25, 131].

(2) Mobile phones are among the product groups that appear to largely escape the official collection and recycling systems. Take back rates of formal collection systems are traditionally below 20% [29][41]. This can also be seen in table 3.3, where mobile phones accounted for less than 1% of the mass of ICT waste collected at municipalities. The small size of mobile phones allows for easy disposal in the household waste and storage over long periods of time, as opposed to bulkier products, e.g. EOL monitors, PCs and white goods. Recent data suggests that most consumers either store their phone or give it someone else after the first use phase [28]. Mobile phones are used for up to another six years by second and third consumers. A number of collection programs in different regions have shown that it is challenging to motivate consumers to hand back their EOL phones. Factors that support consumer willingness to return EOL mobile phones are ease of use/convenience, strong messaging/consumer education and incentives, according to a study by Nokia [168].

[41] For comparison, the collection rate of LCD monitors and CE is > 40% of WEEE generated [80].

(3) In addition to absence of successful strategies for EOL mobile phone collection, previous research has shown that traditional mechanical pre-treatment of mobile phones is not optimal to reclaim raw materials from EOL mobile phones [78]. The study of [78] shows that the combination of depollution and metallurgy is the most favorable recycling route from a value recovery standpoint, and the second most favorable in terms of environmental performance, compared to three alternative EOL routes (manual disassembly, mechanical treatment and landfilling)[42]. However, most EOL phones are currently pre-processed along with the mixed WEEE stream in mechanical processes [31]. It is also estimated that many EOL mobile phones are donated or resold to developing countries, where efficient recycling infrastructure does not exist [153].

In summary, the data shows that there is currently a large gap between the perceived importance of mobile phone recycling, and the reality of collection and recycling rates. Poor performance of current programs on the one hand, and substantial potential in terms of value and resource recovery on the other, may lead OEMs to invest in programs specifically tailored to EOL mobile phone collection. These programs would need to overcome the weaknesses of the current collection systems, for example educate consumers on mobile phone recycling, provide incentives for consumers, provide convenient disposal options and optimize the choice of treatment processes.
Designing and implementing a program for EOL mobile phone collection would require financial investments beyond the costs of traditional WEEE take back programs, as well as time investments for the development of e.g. consumer education strategies and collection logistics. The question that provokes the modeling of the scenarios is as to whether these investments would 'pay off' for OEMs in terms of AEB performance[43]. The commitment of OEMs to improve AEB performance is the prime motivation for developing scenarios. These scenarios are able to give guidance on how collection programs could potentially be designed.

The key questions are:
Question 1 (Comparison of scenario 1 and mixed ICT waste case): Would focusing on one specific EOL product substantially increase AEB performance in order to justify the additional investments, which an EOL mobile phone collection program demands?
Question 2 (Comparison of scenario 1 and scenario 2): If so, to what extent do these improvements depend on the choice of a specific recycling process?

[42] Environmental performance of 'direct smelting' is surpassed by 'manual disassembly', but the economic performance is 16 times higher for the 'direct smelting' route.
[43] This work does not apply any economic metrics to evaluate take back programs, so the use of the term 'pay off' is to be understood in a qualitative sense.

Question 3 (Comparison of scenario 1 and mixed ICT waste case): Does high concentration of PM and copper in mobile phones compensate for the 0% recovery of steel and aluminum in the metallurgical process, given that steel and aluminum recovery accounted for the majority of CED, CExD, EF and GWP savings in the mixed ICT waste case?
In developing scenario 1 and 2 the AEB of an exclusive EOL mobile phone collection program can be quantified. In selecting two different processing routes, the results of scenario 1 and scenario 2 can be compared against each other and compared against the mixed ICT waste case.

4.2 Variables

Three parameters are of importance in both scenario 1 and 2: mass M_{in} of substance i fed to two different processes, which are characterized by their recovery rates k_i. The following chapter outlines the main assumptions behind the system variables and data inputs for the scenarios.

4.2.1 Basic Assumptions

Municipal recycling systems currently collect EOL mobile phones along with the mixed WEEE stream. Despite research showing that the optimal recycling route for phones is direct processing in a copper smelter, the reality shows that recyclers cannot manually separate the phones from the incoming mixed WEEE containers. This results in the phones being treated along with other product groups. The advantage of an exclusive mobile phone collection program is that the phones can be steered towards the optimal process. An overview of the input, processes and material flows modeled in the scenarios can be seen in figure 4.2.

Scenario 1 involves manual removal of the battery (depollution) and processing at the copper smelting facility. In this case, it is assumed that there is no manual disassembly of e.g. plastics, as the labor cost for dismantling would exceed the additional value returns (in a European setting of the scenario) [78]. There is also no mechanical disassembly (e.g. shredding, automated disassembly), but the phones are processed at a copper smelter facility directly after depollution. Batteries, chargers and other mobile phone accessories are not considered in the calculations, so the material data outlined in table 4.1 refers to handsets only. At the smelting facility, the phones are typically shredded to prepare the feed material for the smelter [91]. Contrary to the pre-processing of mixed WEEE, no material is separated after shredding, but all of the scrap is fed to the metallurgical process. The shredding process is also an isolated system, which means that dusts remain with the scrap. The material is then fed to a furnace. Along with copper, gold, silver and palladium the recovered substances also include e.g. lead, zinc and platinum. However, this scenario only looks at recovered cooper, silver, gold and palladium to enable comparison with the mixed WEEE case. Ferrous materials and aluminum are not recovered in the copper smelter and are transferred to the slag [37].

Scenario 2 describes a case in which the phones are depolluted and then shredded at a traditional pre-processing facility (similar to the one in the empirical case). As opposed to the ICT waste case, scenario 2 assumes that shredder feed consist of EOL mobile phones only, so the phones are not shredded along with other types of WEEE. After shredding, the scrap is processed over a number of separation steps to seperate ferrous metals, aluminum and other non-ferrous metals. The ferrous metals and the aluminum output streams are then sent to end-processing facilities, where secondary steel and aluminum are produced from the scrap. The copper/PM-rich output is end-processed at a copper smelter to produce secondary gold, silver, palladium and copper (amongst others). The material input data refers to handsets only (without battery and accessories). As opposed to scenario 1, the total yield of raw materials recovered in scenario 2 is influenced by the recovery rate of two types of processes, (mechanical) pre-processing and (metallurgical) end-processing.

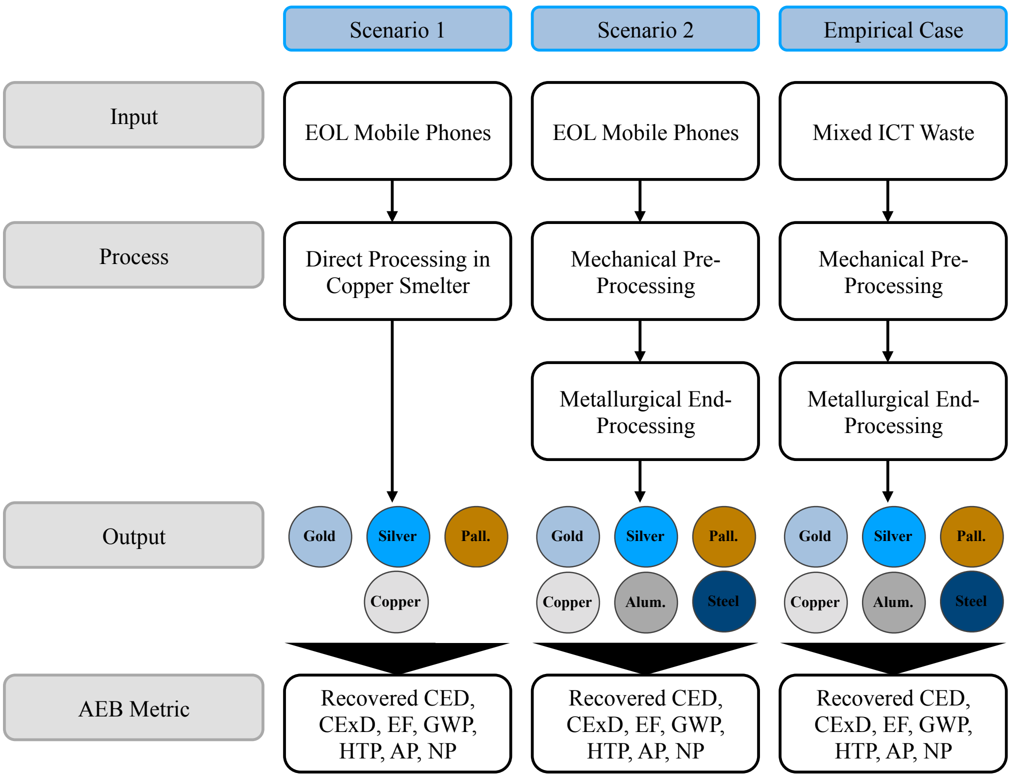


Figure 4.2: Overview of Material Flows in Scenario 1, 2 and the Mixed ICT Waste Case

4.2.2 Data Input

Data input to the scenario consist of material data, process data and environmental data (see Table 4.1). Material data includes data on the average product composition of EOL mobile phones and a value for the mass fed to the process. The overall mass of EOL phones fed to the process is fit to the mass of mixed ICT waste fed in the empirical trial to enable comparison. Process data covers the recovery rate of gold, silver, palladium, copper, aluminum and ferrous metals in mechanical pre-processing, the estimated recovery rates of a copper smelting process, secondary aluminum production, as well as secondary steel production. Data input to the EB variables (environmental data) is obtained from the ecoinvent database and identical in both scenario calculations and the mixed ICT waste case.

Scenario 1			
Material Data	**Substance Concentration**	**Unit**	**Reference**
Ferrous Materials	7	%	[24]
Aluminum	1	%	[69]
Copper	13	%	[24]
Gold	347	ppm	[24]
Silver	3630	ppm	[24]
Palladium	151	ppm	[24]
Feed Mass	29,958	kg	
Process Data	**Recovery Rate**	**Unit**	**Reference**
Ferrous Materials	0	%	[77]
Aluminum	0	%	[77]
Copper	95	%	[77]
Gold	98	%	[77]
Silver	97	%	[77]
Palladium	98	%	[77]
Environmental Data	see table 4.5		

Scenario 2			
Material Data	**Substance Concentration**	**Unit**	**Reference**
Ferrous Materials	7	%	[24]
Aluminum	1	%	[69]
Copper	13	%	[24]
Gold	347	ppm	[24]
Silver	3630	ppm	[24]
Palladium	151	ppm	[24]
Feed Mass	29,958	kg	
Process Data	**Recovery Rate**	**Unit**	**Reference**
Pre-processing			
Ferrous Materials	90	%	[31] [176]
Aluminum	60	%	[176]
Copper	60	%	[31] [176]
Gold	25	%	[31]
Silver	25	%	[31] [176]
Palladium	25	%	[31]
End-processing			
Ferrous Materials	89	%	[51]
Aluminum	60	%	[192]
Copper	95	%	[77]
Gold	98	%	[77]
Silver	97	%	[77]
Palladium	98	%	[77]
Environmental Data	see table 4.5		

Table 4.1: Data Input for EOL Mobile Phone Scenarios

4.2.2.1 Material Data

Data on the concentration of the six target substances in mobile phones is available from a number of literature references [24, 69, 77, 78, 124, 127, 183], which are shown in table 4.2. For this study, a dataset which represents the average composition of mobile phones is selected [24]. This data is based on multiple assays of several t of mobile phones. The original dataset does not provide an explicit value for aluminum concentration, so an estimate was made, based on a reference by the same author [69]. The reason for selecting average material composition data is that all other datasets represent only an example of what the material composition of one mobile phone can be.

Reference	**[77]**	**[24]**	**[78]**	**[183]**	**[69]**	**[124]**	**[127]**	
Year of Production	**2000**			**1995-1996**	**1999**	**2005**	**1997-2006**	
Material								**Unit**
Ferrous metals	2.4	7.0	8.0	3.7	5.0	3.0	3.5	%
Non-ferrous metals								
Copper	26.8	13.0	14.2	15.6	13.0	15.0	33.3	%
Aluminum	2.3		2.9	1.8	1.0		1.5	%
Gold	800.0	347.0	380.0	245.0	350.0		1455.3	ppm
Silver	800.0	3630.0	2430.0	4800.0	1340.0		8252.1	ppm
Palladium	610.0	151.0	150.0	0.0	210.0		376.3	ppm
Other		4.2	4.2	10.3	0.9	4.0		%
Other								
Plastics	44.0	41.0	59.6		57.0	58.0		%
Glass	5.5	34.0	10.6		2.0			%
Other	18.4		0.2		21.0	20.0		%
Note		Average mobile phone composition				Other: nickel, zinc, silver and its compounds	Data refers to PCB only, mean values of 19 samples	

Table 4.2: Comparison of Literature References: Gold, Silver, Palladium, Copper, Aluminum and Ferrous Concentration in Mobile Phones

The data shown in table 4.2 indicate that this type of product data varies significantly. The material composition depends on model and make, but also on the year of production [78][44].

For example, table 4.3 shows that silver and ferrous concentration in PCBs from mobile phones varies greatly, whereas the concentration of copper and gold varies much less. The data was obtained from the study by [127] and is based on analysis of PCBs from 19 different mobile phones. Although the data only covers the material composition of the PCBs, the analysis demonstrates the variability of product BOMs. This finding supports the approach of using data that captures the average composition of mobile phones.

Substance	**Mean Concentration**	**Unit**	**CV**
Silver	8252	ppm	0.95
Gold	1455	ppm	0.20
Palladium	376	ppm	0.66
Copper	33	%	0.16
Aluminum	2	%	0.53
Ferrous	4	%	1.09

Based on data obtained from [127]

Table 4.3: Mean and coefficient of variation (CV) for Gold, Silver, Palladium, Copper, Aluminum and Ferrous Concentration Detected in 19 Different PCBs from Mobile Phones

[44] The fact that material concentrations vary by year of production is also illustrated in the study of [78] who compares the average composition of mobile phones built in 1999 and 2003 and shows that the concentration of PM decreased by 60% (silver), 25% (gold) and 35% (palladium).

The total mass of gold, silver, palladium, copper, aluminum and ferrous in the input material is calculated by combining the absolute mass of the input material with the concentration values.

4.2.2.2 Process Data

Mechanical Pre-Processing: Recovery rates of the process modeled in scenario 2 are more difficult to obtain than recovery rates of metallurgical processes. In mechanical pre-processing, recovery rates largely depend on the disassembly and separation technology. In other words, the recovery rates vary by facility. Although scenario 2 and the mixed ICT waste (empirical) case compare in terms of processing technology and recycling path, the 'best-case recovery rates' assessed in the empirical trial are not useful for application in scenario 2. If used as input for variable k in scenario 2, the recycling rates of pre-processing are likely to be overestimated. This is because the 'best-case recovery rates' are based on assaying of only 50% of the total output fractions from the trial. A number of literature references provide recovery rates for different substances in mechanical pre-processing of WEEE. An overview of these values is shown in table 4.4.

Material	**[30]**	**[181]**	**[72]**	**[119]**
Ferrous Metals	71%	90%	<95%	n.a.
Aluminium	n.a.	90%	<95%	n.a.
Copper	60%	50%	<95%	n.a.
Gold	25%	10%	n.a.	75%
Silver	12%	n.a.	n.a.	70%
Palladium	26%	n.a.	n.a.	40%
Note	Mixed WEEE feed	PCB feed, 'Intense Shredding' Scenario	Mixed WEEE	PC only feed

Table 4.4: WEEE Pre-processing Recovery Rates – Empirical and Modeled Values from Different Literature References

Some data are based on empirical trials [31, 119], some data is modeled [181] or based on estimates [72]. The pre-processing technology and process steps described in these references is not identical, for example, in [119] the feed is processed in a smasher in order to liberate the PCBs prior to shredding[45]. In [31], the feed is directly processed in a shredder (similar to the empirical case in chapter 3 and similar to the estimated conditions in scenario 2). The study of [31] also provides the most comprehensive dataset in terms of substances analyzed and gives detailed information on how the data was obtained, and was therefore used as the main reference for this study. Some of the values were rounded based on expert guidance [176], for example the rate for all PM was estimated to be 25%, 90% for ferrous, and 60% for copper and aluminum.

[45] A smasher consists of a rotary drum, which is used to liberate certain components from WEEE.

Metallurgical End-Processing: As in the mixed WEEE case, recovery rates of a copper smelting plant are obtained from [77]. In this study, the term 'recovery' implies the production of secondary material, which perfectly replaces primary material. Ferrous materials and aluminum contained in copper smelter slags find application in the production of building material but cannot be recycled into the original material. The recovery rate for these substances therefore is zero. The same recovery rates as in the mixed ICT waste case were applied for aluminum and steel scrap smelting and refining (see table 4.1).

4.2.2.3 Environmental Data

Appendix D shows the datasets that were selected from the ecoinvent database to obtain values for secondary and primary materials. These datasets were used for the analyses of the ICT waste case. The same environmental data was used for the scenario analyses. Table 4.5 gives an overview of the AEB of gold, silver, palladium, copper, aluminum and steel in seven environmental impact categories.

Material	Recovered CED (MJe/kg)	Recovered CExD (MJe/kg)	Recovered EF (m2a/kg)	Recovered GWP (CO2e/kg)
Aluminum	169.3	190.5	28.0	11.0
Copper	31.5	246.4	4.8	1.3
Ferrous Metals	21.1	30.9	3.9	1.6
Gold	304,980.3	743,942.7	56,018.7	17,843.5
Palladium	162,464.0	203,964.3	28,937.2	8,972.6
Silver	6,569.6	13,608.3	1,216.8	424.5

Material	Recovered HTP (kg 1.4-DCBe/kg)	Recovered AP (kg SO2e/kg)	Recovered NP (kg PO4e/kg)
Aluminum	56.5	4.8E-02	4.3E-03
Copper	633.5	0.5	0.5
Ferrous Metals	9.8	6.2E-03	1.6E-03
Gold	391,502.8	190.7	1,066.9
Palladium	17,146.2	8,535.4	15.7
Silver	4,440.2	6.7	12.5

Table 4.5: Overview of Environmental Data Used in Scenario 1, 2 and the ICT Waste Case

4.3 Results

Table 4.6 shows the results of the recovered mass in both scenarios.

Material	Mass Recovered in Scenario 1 (kg)	Mass Recovered in Scenario 2 (kg)	Mass Recovered in ICT Waste Case (kg)
Ferrous Metals	0.0	1,679.7	8,290.5
Aluminium	0.0	107.8	319.1
Copper	3,699.8	2,219.9	763.4
Gold	10.2	2.5	0.1
Silver	105.5	26.4	1.2
Palladium	4.4	1.1	<0.1
Total	**3,819.9**	**4,037.4**	**9,374.3**

Table 4.6: Secondary Raw Material Yields of Scenario 1 and Scenario 2

The results show that the recovered mass is largely dominated by secondary copper in scenario 1 and by copper and ferrous metals in scenario 2. The mass yield of scenario 1 is 13% and the mass yield of scenario 2 is 14% compared to the overall weight of the input to the process. In fact, even if this analysis looked at all of the materials contained in EOL mobile phones, the total yield of recycling scenario 1 would not be higher than 20% of the input mass, because glass and plastics (which account for about 75% of the input) are transferred to the slag in a copper smelting process. Although ferrous metals and aluminum are recovered in scenario 2, the total yield in this scenario is only slightly larger than in scenario 1. The amount of PMs recovered in scenario 1 is 120 kg, of which the largest share is silver (88%). Scenario 1 recovers about 80 times more PMs than the ICT waste case. The amount of precious metals recovered in scenario 2 is 30 kg, so only about 25% of the precious metals yield of scenario 1, but over 20 times as much as in the ICT waste case.

The AEB methodology was applied to the mass yields of secondary steel, copper, aluminum, gold, silver and palladium calculated in scenario 1 and 2. The sum of the AEB in each impact category was compared against the sum of the AEB in the ICT waste case. The results of this comparison are shown in figures 4.3 to 4.6. The most apparent result of the analysis is that scenario 1 is the most favorable option in terms of AEB performance in all environmental impact categories. This is a result of the high concentration of PM in EOL mobile phones and their high recovery rates in direct metallurgical processing. On a more granular level, the data shows that the largest share of AEB comes from the recovery of gold in the CED (67%), CExD (70%), GWP (67%) and EF (68%), NP (76%) and HTP (58%) in scenario 1. While not being the largest source of recovered HTP, copper also accounts for a major share (34%) in the HTP category because of the high mass flow and extensive SO_2 emissions in primary copper production. The only category where gold plays a minor role is AP, for which palladium covers 90% of the total recovered AEB. As mentioned before, this demonstrates that the efficient recovery of gold, copper and palladium must be the utmost priority in mobile phone recycling.

In terms of total AEB, the second most favorable take back and recycling option is not consistent in all categories. While the ICT waste scenario shows higher or about equal values in the CED, CExD, EF and GWP categories, scenario 2 shows better results in terms of recovered AP, NP and HTP. This is largely a result of the high mass flow of copper in the mobile phone input and higher yields of copper in scenario 2 than in the mixed ICT waste case. There was at least 1,511 kg of copper in the mixed ICT waste batch and around 3,894 kg was estimated to be in the process feed material in scenario 2. Even though the overall efficiency of the recycling chain (pre-processing and end-processing in copper smelter) was only 57% for copper in scenario 2, the total recovered mass is still larger than in the ICT waste case and results in high recovered HTP, AP and NP.

Overall, the results of the scenario analysis can be interpreted as follows: Compared to scenario 2 and the ICT waste case, a collection program such as the one described in scenario 1 is by far the most favorable option from an environmental standpoint and the most effective way to significantly improve AEB performance. In terms of environmental performance, the success of an EOL mobile phone collection program fundamentally depends on the choice of recycling process to recover secondary raw materials. Although the results are not consistent across all impact categories, it can be concluded that OEMs could as well just continue to limit collection programs to mixed WEEE, rather than investing in an EOL mobile phone recycling program, if the recycling rates of pre-processing are as low as in scenario 1. Scenario 2 shows better results than the ICT waste case only in the AP, NP and HTP categories, but the difference is not nearly as significant as the difference between scenario 1 and the other cases.

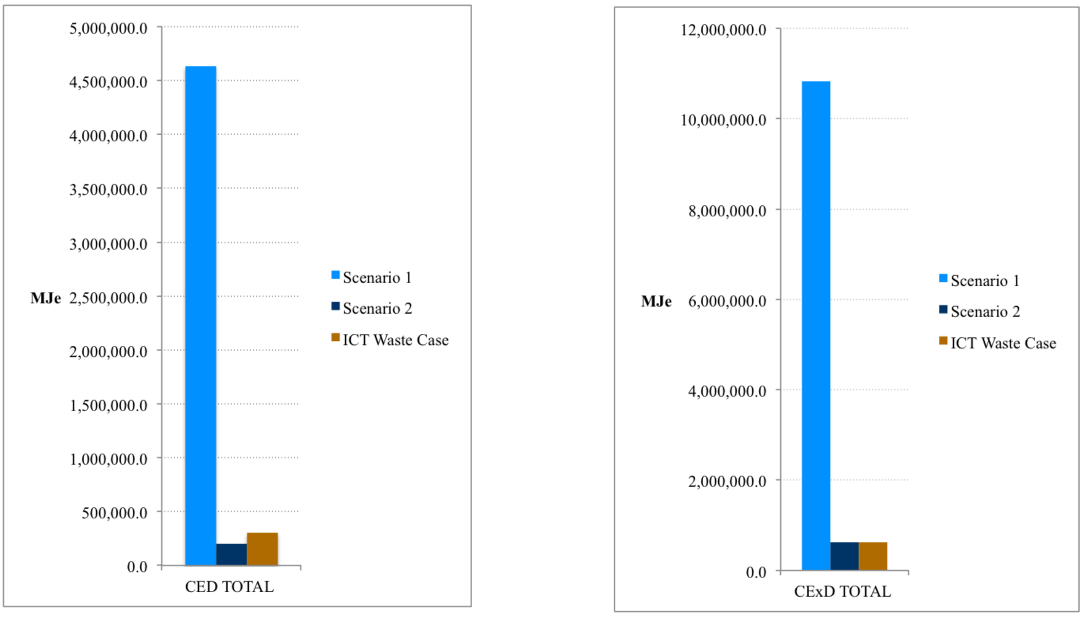


Figure 4.3: Comparison of Total Recovered CED/CExD in Scenario 1, 2 and the ICT Waste Case

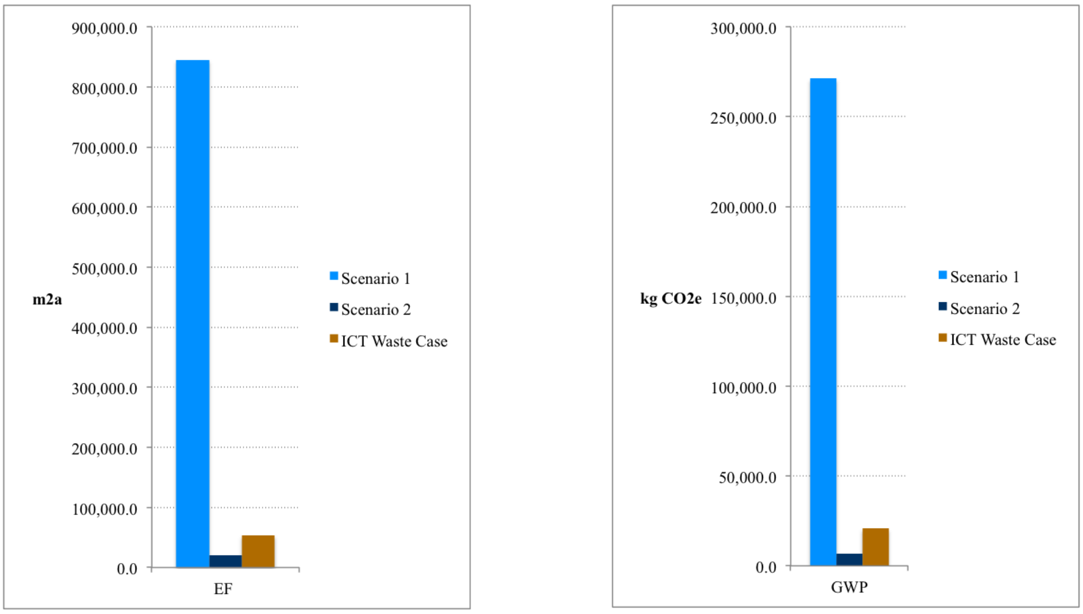
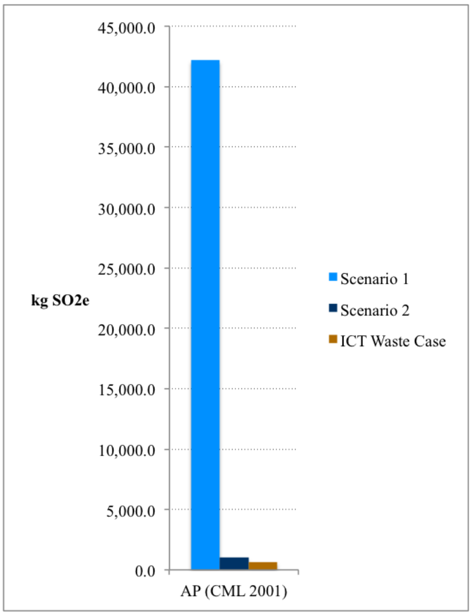


Figure 4.4: Comparison of Total Recovered EF/GWP in Scenario 1, 2 and the ICT Waste Case



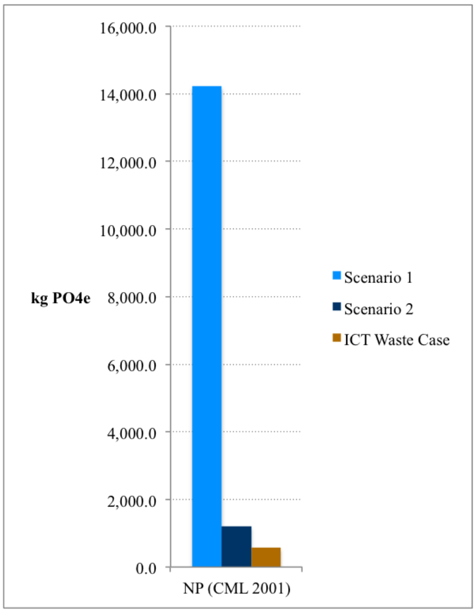


Figure 4.5: Comparison of Total Recovered AP/NP in Scenario 1, 2 and the ICT Waste Case

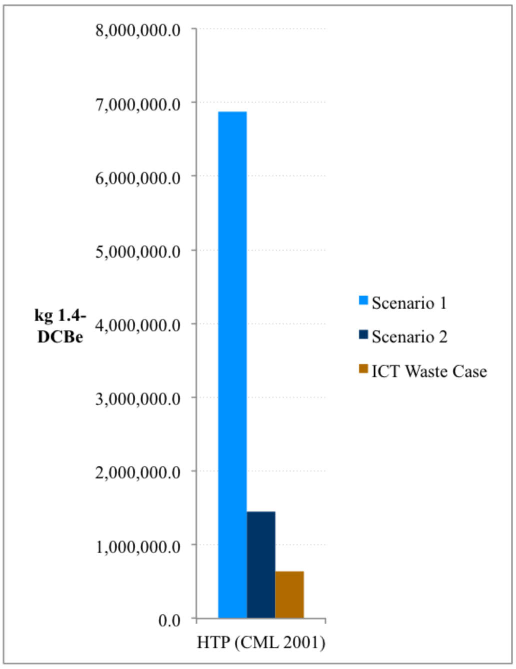


Figure 4.6: Comparison of Total Recovered HTP in Scenario 1, 2 and the ICT Waste Case

4.4 Discussions

The previous chapter has shown that the development of scenarios is a straightforward approach for OEMs to estimate the AEB performance of future take back programs and to organize collection and recycling based on environmental considerations. The development of scenarios can thus support decisions in the planning stage of take back programs. The scenarios developed in this study are a good example for a case in which the collection of a specific type of EOL material can lead to significant AEB improvements, but also to disadvantages or less significant improvement, depending on the choice of the recycling process. The key learning from this analysis is that collection of environmentally burdensome materials is not an environmental 'win' per se, but that the most efficient process for the specific waste must be chosen.

The choice of the scenarios was largely based on the availability of process input and recycling rates data. The material data available for mobile phones is extensive and detailed, compared to other product categories (as can be seen in appendix B). Recovery rates of different recycling processes are also difficult to obtain and are currently limited to just a few empirical studies, which are shown in table 4.4. The recovery rates estimated for mechanical processing of EOL mobile phones are to be regarded as approximate values. More complex scenario analysis can be conducted with commercial models, such as QWERTY [77].

One aspect that complicates scenario analyses is that the most and least favorable scenario is not always consistent across all impact categories. This can be seen in the scenario analysis developed in this study, in which the second most favorable option is scenario 2 in considering AP, NP and HTP, and the ICT waste case in considering e.g. the CED, EF and GWP categories. If the results of scenario analyses were used in the planning stage of recycling programs, OEMs would necessarily have to decide which type of avoided impact they prioritize. Furthermore, even if OEMs incorporate environmental considerations into the design of take back and recycling programs, it must be acknowledged that economic factors (cost of collection, cost for processing, value returns of recycling process) are at least as important as AEB performance.

4.5 Conclusions

In order to answer one of the questions stated in section 4.1 (Would the investments into the design of a mobile phones take back program 'pay off' in terms of AEB performance?), it can be concluded that the investments are worthwhile if the choice of processing is that of scenario 1, instead of the process described in scenario 2. Compared to the mixed ICT waste, EOL mobile phones intuitively seem like a more relevant product category in terms of secondary raw material recovery because of their high concentration of precious metals. However, the analysis shows that this potential is only tapped if the optimal recycling path is chosen. Overall, the AEB metric has proven to be an effective tool to quantify the environmental benefit of different programs and can be used to inform strategic decisions on future take back programs.

5 Results and Recommendations

In the last chapter of this thesis, the main results of the research will be summarized and discussed in light of the research questions and metrics criteria outlined in chapter 1. While some of the strengths and weaknesses of the methodology, empirical trial and scenario analysis were discussed at the end of the respective chapters, the following part of this thesis will raise some overarching points of discussion that concern this work. Some of the findings of this research can be translated into recommendations, which concern producers of electronics on the one hand, and policy makers on the other hand. Moreover, the empirical trial revealed some relevant findings for the analysis of WEEE and recycling processes, which is why some recommendations are addressed to the operators of recycling facilities. This research has also shown that there are many opportunities for future research, of which some will be discussed at the end of this chapter.

5.1 Summary of Results

Two research questions were posed at the beginning of the thesis: (1) How can producers measure the performance of WEEE collection and recycling programs, irrespective of mass and units collected? (2) How can indicators of environmental impact be incorporated into these alternative performance metrics? Below is a summary and critical discussion of how these questions were answered.

5.1.1 Research Questions

The work presented here has shown that the AEB metric is capable of measuring the environmental impact of WEEE collection and recycling programs and is an alternative to the widely used mass and unit based performance metrics that were shown in subsection 1.2.4. The five key findings of analysis are:

(1) The metric is not entirely independent of the mass of WEEE that is collected and recycled because more WEEE will potentially result in higher avoided environmental impacts. What sets the AEB metric apart from traditional metrics is that performance improvement is not exclusively coupled to increased collected volumes, but to numerous parameters in the recycling system.

(2) In reality, producers cannot influence all of these parameters (e.g. the environmental impact of primary production), but they have influence on some of them. Perhaps most importantly, the research has shown that by increasing the rate at which materials are reclaimed in recycling, the performance of collection programs could be improved significantly. For example, in the empirical case it was shown that there

is a large potential to increase the effectiveness of collection programs by increasing the material recycling rate in pre-processing. The improvement potential in this case ranged from 40% in the GWP (IPCC 2007) category to 94% for AP (CML 2001).

(3) Focusing on improved recovery of precious metals is of major importance in terms of performance improvement, but the largest share of the total AEB still comes from the recovery of steel, copper and aluminum. This is true for the current ICT waste stream, but the material composition of this waste stream will change in the future and has to be reevaluated. Due to miniaturization of ICT products, it is likely that there will be a shift from ferrous metals to non-ferrous metals (e.g. PM, copper).

(4) The application of numerous environmental impact categories shows that 'energy' is not a sufficient stand-alone indicator to describe the avoided environmental burden that results from secondary materials production. While CED, GWP and EF largely correlate in combination with the results of the mixed ICT case, the CML 2001 categories and CExD underline the importance of copper recycling. The results actually show that it is complicated to decide for or against the recovery of one material and that all depends on the environmental impact category that is considered to be a priority.

(5) When a program collects exclusively mobile phones and recovers the most 'environmentally burdensome materials' at a high rate (scenario 1), the avoided environmental impact is significantly higher than for a program that collects mixed ICT waste[46]. However, scenario 2 shows that the collection of the most environmentally burdensome materials is not a gain for the environment 'per se', and can in fact even turn out less effective than the collection of mixed ICT waste, if suboptimal processes are selected for treatment.

Although the empirical trial is meant to illustrate a 'standard case' of municipal WEEE collection and recycling in Europe, it is essentially to be understood as a test case to validate the methodology. The same is true for the modeled scenarios. There would certainly be countless other opportunities to develop scenarios and empirical trials. In the end all cases show that what matters in the design of a program is that the processes are tailored to the type of WEEE that is collected.

5.1.2 Effectiveness of Proposed Metric

In subsection 1.2.3 a selection of criteria to consider in the development of metrics were discussed and the AEB metric can be compared against these criteria.

[46] The scope of the analysis includes six materials, of which the three precious metals (gold, silver and palladium) are considered as 'environmentally burdensome materials' in the context of this work. This is because of the much larger difference between impact of primary and secondary material per kg of material than in the other materials (steel, copper and aluminum).

(1) The **usefulness** of the metric can be demonstrated by comparing the findings of the overall analysis with the factors that were defined as 'the goals of recycling' in subsection 1.1.3. This comparison shows that the metric helps corporations to achieve two out of three key goals of WEEE collection and recycling: environmental impact minimization and management of corporate reputation. The metric can have a lasting impact on the design of take back programs, which determines the environmental performance of WEEE collection and recycling. The benchmarking analysis showed that a surprisingly small number of ICT companies report on material flows after collection, and even less on the materials that get recycled from WEEE. None of the companies that were analyzed provided any type of environmental measure for WEEE collection and recycling, so the implementation of the AEB metric would set a producer apart from the industry trend. Data on the environmental impact of collection programs is more than legislators and other stakeholders expect from corporate reporting in this field and demonstrates commitment beyond compliance and common practice. As for the third goal of recycling, the metric does not respond to the current reporting requirements set by legislators. As long as legislators use mass based metrics, environmental impact metrics will have smaller chances of being implemented in the industry.

(2) The key objective of the methodology proposed in this research is to assess the environmental impact of recycling and to demonstrate how this positive impact can be increased. Most of the parameters that influence performance are related to efficiency (e.g. material recycling rate, collect the most environmentally burdensome materials), which is **in line with the resource efficiency objectives of European policy makers**. The metric motivates producers to make environmentally informed choices when selecting recycling vendors for WEEE collection programs,

(3) The methodology of comparing the impacts of primary material production with that of secondary materials production is a straightforward, **easy to use** approach that does not underlie a complicated model. As opposed to mass and unit based metrics, the AEB metric definitely needs to be accompanied with more information of the methodology when used for internal and external communication. If this information is concise and well structured, the AEB metric is **easy to communicate**.

(4) The AEB metric is rather **complex in terms of data input**. For most of the parameters that underlie the methodology very few data is available. While the environmental impact data (EB_p and EB_s) is comparatively good (although data is only available for few materials, lack of data is specifically the case for recycled materials), data on the recycling rates of different processes as well as data on the material composition of EOL products is very difficult to obtain. The AEB metric definitely involves a much larger amount of data than mass based metrics. While primary data on the mass of WEEE collected is a regular part of producer's take

back programs, primary data on material recovery rates (ICT waste trial) or the material composition of WEEE (appendix C) is costly and complex to assess.

(5) As a consequence of the common reporting practice of the industry, the AEB metric does not enable benchmarking of performance and is thus not **comparable**. Even if multiple companies reported the performance of their take back programs in environmental terms, there would have to be a standard methodology and data sets to make benchmarking possible.

(6) The AEB metric is **diagnostic** in that it helps to identify the weaknesses of WEEE collection programs and can even be a helpful tool in the program design process. The methodology that underlies the AEB metric delivers insights into the many parameters that determine the magnitude of impacts that can be avoided through EOL product recycling.

5.1.3 Discussions

This research has shown that the AEB metric is useful to quantify the environmental impact of WEEE collection and recycling programs, and to analyze which parameters in the recycling system influence the overall environmental effectiveness of industry WEEE collection programs.
One of the baseline assumptions in this work is that producers require metrics to improve recycling programs beyond legal obligations. It can be argued whether or not there is an incentive for producers to 'care' about the type of products they collect, the processes in which the WEEE gets recycled and the rate at which materials are recovered. For one, especially in the EU, there is an increasing amount of legislation that affects producers of electronics and it can be assumed that efforts to be compliant impede voluntary measures. Secondly, in a sector with high safety and occupational health risks, such as the recycling sector, OEMs will consider EHS a priority when engaging with recycling vendors. While both arguments are valid, they do not consider the strategic importance of secondary raw material supplies for the electronics industry. Given the rapid development of technology and the potential (and largely unpredictable) demand for technology materials, it is advisable for producers to understand the capacities, technologies and structure of the 'reverse supply chain'. From a producer's perspective, 'caring' about the recycling industry and downstream processes is probably a long-term investment, but OEMs that have built knowledge in recycling technologies will clearly benefit from this understanding in a future of unforeseeable supply and demand. On a further more general note: The discussions that took place with operators of different types of recycling facilities and many producers over the course of this research showed that there is few, if any constructive communication between the electronics and the recycling industry. The AEB metric can be a tool to encourage these industries to collaborate and share information in terms of product make and material composition of products on the one hand, and technological

challenges to recover materials from complex products on the other.
Another concern that might be raised is the fact the largest environmental impacts (in terms of energy consumption and GHG emissions) in the life cycle of many electronic products occur in manufacturing (e.g. ICT) [32,126] or in the use phase of a product (e.g. white goods) [160], which could lead to the question of whether or not it is a priority for OEMs to put effort into the environmental assessment of product EOL. It is important to clarify that the research question posed at the beginning of this work, and the methodology that was developed to respond to it, are not meant to compensate any efforts that producers should undertake to decrease the environmental impacts of electronics manufacturing or increase the energy efficiency of products. Such measures are of major importance, but the fact that production and use are the environmental hot spots in the life cycle of a product, should not abstain OEMs from engaging in areas of comparably lesser impact.
The methodology that underlies the AEB metric is based on two assumptions that need to be discussed. The first assumption is that secondary materials are able to perfectly replace primary materials, in a sense that the materials are able to regain their original material characteristics (e.g. functionality, substance composition). As mentioned before, this comparison can only be made for metals, as the plastics contained in WEEE typically get downgraded in recycling. For glass, which mainly comes from CRTs in the current mixed ICT stream, very few options still exist for glass-to-glass recycling [170]. In many cases the glass is decontaminated, grinded and used for the production of building materials. Other materials (typically wood and cardboard) are incinerated. The second assumption is that mining, primary production and the resulting environmental impacts are 'avoided' through the recovery of secondary raw materials from waste. This implies that less virgin material is produced and thus less emissions and raw material consumption is needed for materials production overall. In a system where many metals are mined as a by-product or coupled with other elements, this assumption is not entirely realistic. Simply speaking, the economics of metal mining are more complicated than the assumption that decreasing demand (as a result of increased secondary production) will result in less primary production and thus 'avoid' environmental impacts. For example, the majority of the global production of silver is mined as a by-product of copper, lead and zinc [1]. The primary production of silver therefore heavily depends on the demand for the main metals, and declining demand for silver would likely not influence the amount of silver that is produced, but the price at which silver is traded on the commodity market. That is, even if more silver were recycled from waste, there would be greater supply (which would influence prices), but greater supply alone would not affect the amount of silver that is produced from virgin ore. However, even if the reality of materials production and the mechanisms of the markets are more complex than the proposed methodology probably implies, the effectiveness of the metric is not impaired. Quantifying the environmental impact of primary production and comparing this impact with recycling creates more awareness for the extensive resource consumption and emissions resulting from mining,

smelting and refining of ores. For example, amongst the materials that were analyzed in this study, the CED of primary material production is between twice (copper) and 51 times (silver) as large as the CED of secondary materials production. In any case, even if recycling does not prevent mining under the current market conditions, recycling is the more resource efficient option. If the AEB metric motivates producers to reconsider their choices in recycling programs and opt for more efficient processes, it is in fact not relevant if the assumptions behind the metric represent economic reality.

5.2 Recommendations

While the original intention of this research was to develop performance metrics for producers, the research uncovered some aspects that are of interest for operators of recycling facilities. Some of the following recommendations are also addressed to policy makers.

5.2.1 Recommendations for Producers

The key recommendations for producers can be loosely classified into recommendations concerning program performance metrics and reporting, and some thoughts on the opportunities for collection program design and product information.

The analysis of 22 different corporate websites and sustainability reports has shown that there are major differences between different companies in terms of the amount and quality of information and the emphasis that is put on WEEE collection programs overall. Regardless of the type of metrics that are used to quantify the achievements in WEEE take back; one recommendation would be to be more precise in the reporting overall. In many cases it is not clear if the reporting on collected volumes covers only one region or all of the regions where the company operates, and often the coverage with respect to the type of WEEE that is collected is unclear (i.e. does the company only collect ICT products, of the own make or regardless of make?). If methodologies or terms are used that are not self-explanatory, it is advisable to give a brief definition or explanation. Especially terms such as ‘recovery’, ‘recovery rate’, ‘recycling rate’, ‘resource’ and ‘reuse’ tend to be used loosely and provide no information at all, if not accompanied by more information. The risk that is linked to such nondescript reporting is that consumers and other stakeholders will not consider the information credible.

There is a strong indication that many companies have changed their metrics over the past couple of years. While a couple of US companies used to refer collected volumes to previous sales [6], some of these companies have changed their metrics to absolute mass based metrics. There are likely a number of reasons why the companies decided to change their metrics. One argument could be that generic product lifetime assumptions, which underlie these metrics, are in fact not realistic. Why abandon the metric completely if it could be improved? It is strongly recommended that producers reevaluate lifetime assumptions, as there is obviously a difference between the lifetime of a mobile phone and that of a computer. With respect to product specific lifetimes, it is questionable if mobile phones are really discarded after two years. Assessing average product lifetime is a difficult task, and more research has to be undertaken in this field (see section 5.3). Producers can support this research in assessing lifetimes of EOL products empirically, as they have access to the WEEE that is collected. It would be feasible to do sampling analysis and determine the average lifetimes of products that are found in the waste stream. The sampling methodology proposed in section 3.1 referred to the assessment of product type, but the statistical methods can be used for lifetime assessments as well. Current assumptions seem to be based on a rule of thumb estimate and could be significantly improved with empirical data, in order to enhance the validity of 'mass collected versus mass sold' metrics.

Perhaps most importantly, it is strongly recommended to focus performance metrics on the impacts of WEEE collection and recycling, rather than the action itself. At the heart of any recycling program is the idea that material recovery from waste is a 'better' EOL option than landfilling, so these programs should be evaluated with environmental metrics. The AEB metric is a feasible tool to measure take back and recycling performance, and it can be used complementary with mass based metrics in order to enable benchmarking, but also assess environmental performance.

The AEB metric can be a useful tool for producers to evaluate and improve the quality of recycling programs in a sense that the program set-up can be based on environmental considerations (i.e. choosing the best process for a specific type of WEEE, collecting the most impactful materials). This is a key difference compared to the existing metrics, which encourage producers to focus exclusively on the mass that is collected. Overall, producers should look carefully into their downstream recycling stream because the environmental gain of a collection program is not only determined by the amount (mass) of WEEE that is collected. As for take back programs that are operated by collection schemes in the EU, producers often do not have the possibility to make any choices regarding type of WEEE that is collected and the recycling processes that are used for WEEE treatment. However, at least for voluntary programs, attention can be placed on the way the WEEE is sorted at the collection point and the way different types of products are treated to recover raw materials. As for the data input, producers could contribute to more accurate AEB analysis in making more BOM of EEE publicly available. Such data on the material composition of products would enable more reliable and comprehensive analysis of the materials that are collected and material specific recycling rates. There are currently very few electronics companies that report on materials (e.g. Nokia) [125]. The data that is currently available in the literature is often dated and only valid for one specific type of e.g. PC or mobile phone. As can be seen in appendix B, the variance of material composition data obtained from literature is large. At the same time, there is little data available for many product types, so there are limited possibilities for researchers to assess the representativeness of specific BOMs because the number of samples is not large enough. Producers could support environmental assessments in providing more of such data to researchers or even publicly. The data would not only support assessments such as the one shown in this research or LCA of electronics, but also be utile for operators of recycling facilities. Without knowledge about the material composition of the products that are sold today, the recycling industry and academia has limited possibilities to prepare for the future WEEE stream and to develop suitable recycling processes.

5.2.2 Recommendations for Operators of Recycling Facilities

The empirical case study conducted by this dissertation and described in chapter 3 led to some useful findings and recommendations for operators of recycling facilities. The preparation of the trial was accompanied by a series of detailed discussions with different recyclers about the WEEE recycling system overall and the role of the recycling industry in particular. At least some of the following recommendations were made as a result of these discussions.

As is shown in section 3.1, the statistical methods that were used to assess the representativeness of the sampling results are straightforward to apply and provide robust results. Sorting of only 30 t of WEEE led to some useful findings in terms of the current ICT waste product mix. It was also shown that the representativeness of the results does not increase exponentially with the amount of ICT waste that is sampled. Furthermore, it was demonstrated that the size of the overall population is not a relevant parameter for the representativeness of the results. To date, many recyclers calculate sampling sizes based on the amount of WEEE that is processed overall. This research suggests that this is not useful to increase the representativeness of the results. It is strongly recommended to use simple statistical methods (such as the ones described in this study) to determine the amount of WEEE that needs to be sampled, in order to lower staff cost and decrease the amount of data.

This research has also shown major inefficiencies that occur in a standard WEEE recycling process (pre-treatment) and demonstrated the potential to increase recovered mass and environmental benefits. The economic disadvantage of such inefficiencies is substantial for recycling operations. In the recycling trial at least 40% of the PM were diluted in the ferrous and aluminum output streams. The loss of PM could be significantly decreased if more manual disassembly of PM containing parts (e.g. PCBs) was conducted prior to mechanical pre-processing. There are a number of reasons why recycling operations typically oppose manual disassembly, and one of them is high labor cost for disassembly and sorting. In the recycling trial a number of workers were positioned at different points in the sorting process in order to pick valuable material from the conveyor belts. Given the dilution of PM that is evidentially caused by shredding ICT waste, it would be more reasonable to use some manual labor at the front end of the recycling process and recover at least PCBs. Another obstacle to manual disassembly of PCBs is certainly the issue of poorly sorted containers that arrive from municipal collection points. In reality, it is very labor intensive to isolate products, which contain high value PCBs (e.g. desktop PCs, laptops, mobile phones) from products that are rich in plastics and steel (e.g. printers). It is strongly recommended that operators of recycling facilities articulate this issue to relevant municipal authorities and policy makers.

Another recommendation that concerns the recycling industry is that of more detailed assessments of material specific recovery rates. Most of the data that is assessed by recyclers compares the mass of the input material with the mass of all output fractions, but this data is not useful to understand the rate at which specific materials are recovered from the WEEE. The main barrier to such analysis is that taking samples and assaying of all output streams involves significant cost. As is shown in appendix B and appendix C, the composition of mixed WEEE is difficult to determine, so it is challenging for a recycler to understand the quantities of different materials that are fed to the process. One option to overcome this issue would be to undertake a trial with one single product type (for example mobile phones), for which more accurate estimations of input materials can be made. Such analysis would be useful for recyclers to understand the material recycling rates of the process and show where improvements are necessary.

5.2.3 Recommendations for Policy Makers

The preparation work and sampling analysis that led up to the recycling trial showed that a major share of the WEEE that arrives at recycling facilities for treatment has been liberated from valuable materials at some point in the collection process. The operators of the recycling facility described in chapter 3 estimate that as much as 60% of the EOL products that arrive from municipal collection points are incomplete. This issue was also described by other recycles in the EU that were visited over the course of this research. There is no proven evidence for where this leakage occurs, but it is possible that valuable parts (e.g. copper cables, HDs, PWBs) are removed from WEEE at municipal collection sites. In an industry with low margins, this leads to a significant loss in revenue for the operators of pre-processing facilities, who are left with mainly plastics, glass and ferrous materials for treatment. From a resource conservation standpoint, such leakage results in informal trade of spare parts or valuable materials, which are potentially exported to countries where no recycling infrastructure exists. It is strongly recommended that policy makers undertake efforts to investigate and quantify leakages in the collection system, in order to implement regulatory measures (e.g. penalties) and prevent theft of WEEE in the collection system.

As for the definition of metrics to measure the success of environmental policies, it is strongly recommended that policy makers start defining metrics that measure the impact, rather than absolute in- and outputs. Unfortunately, mass based metrics are still popular to measure environmental performance, e.g. post-industrial waste per USD/EUR in revenue or 'material intensity' indicators (material input as compared to GDP). Metrics and indicators defined by legislators strongly influence the metrics that are used by other stakeholders in the system (see subsection 1.2.4), and policy makers would do well to set examples and move away from mass based targets and metrics. If this is done, standards for the underlying methodologies and data will need to be implemented as well.

5.3 Research Opportunities

This section summarizes critical research areas and knowledge gaps relevant to the development of environmental metrics for WEEE collection and recycling. Some key research opportunities include: **(1) Methods to assess product lifetime**. What are the existing statistical tools (e.g. Weibull distribution)? What other methods and data can be used to estimate the average use-phase of products and predict product EOL? Current industry metrics often refer collected mass to previous sales and the lifetime assumptions that are used for this metric are typically based on a rule of thumb estimate. Regardless of performance metrics, it is crucial for producers and policy makers to understand when specific products become available for collection. On the one hand, it is relevant to align collection and recycling infrastructure to future waste flows, on the other it is critical to understand at what point in time secondary raw material supplies become available for recovery. **(2) Metrics to develop and describe closed loop material systems**. Most of the traditional mass and unit based metrics, as well as the metric proposed in this research, do not link the amount of WEEE that is collected with the amount of WEEE that is POM by a company. Apart from 'mass collected versus mass sold' metrics, what are other measures to compare the WEEE that is collected with the products that were sold some years prior? Are these measures operationally feasible? Are the metrics helpful to guide producers towards the development of closed loop systems? **(3) Methods to educate consumers and incentivize safe WEEE disposal**. Low collection rates, specifically for ICT waste and other small WEEE, underscore the critical need for research in the field of consumer recycling behavior. Which communication strategies can be implemented to effectively educate consumers on the importance of proper WEEE disposal? What is the role of producers in education consumers and creating incentives to return EOL products? How can recycling systems be transformed to make proper disposal of WEEE more convenient for consumers? How can these systems include the informal WEEE streams that exist?

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A Performance Metrics for WEEE Collection and Recycling

The following table shows an overview of the performance metrics that were communicated by 22 companies in the IT, telecommunications and CE sector at the time this research was completed. It is important to note that corporate reporting on environmental issues is usually subject to frequent updates and changes, access dates are therefore given in the reference list. The column 'product coverage' indicates the type of products that were collected. Some companies provide information on worldwide collected WEEE, but some companies disclose information for only selected countries (see column 'Geogr. Coverage')

Company	Metric	Product Coverage	Geogr. Coverage	Reference
Acer	Units recycled (2006-2009), Mass recycled (2006-2009), Recycling Rate (mass-based, no information available on reference values)	PC	Taiwan	(1)
	Mass recycled (2009-2010)	No information	United States	(2)
Apple	Mass recycled as compared to mass sold 7 years ago (2007-2011)	No information	Worldwide	(3)
Asus	Mass reclaimed (collected, reused or recycled) as compared to mass sold same year (2011)	No information	Taiwan, possibly other regions	(4)
Blackberry (RIM)	No information, Units collected (2010) in one take-back program	Blackberry phone	Worldwide	(5)
Dell	Mass recycled (2012)	No information	Worldwide	(6)
Epson	Mass collected (2001-2011)	Products and ink cartridges	Europe, Americas, China, Japan, Asia	(7)
Fujitsu	Units recycled (2010)	PC	Japan	(8)
	Mass processed (2010), "Resource re-use rate" (no further information available)	ICT equipment	Europe, Middle East and Africa (EMEA)	(8)
Hewlett Packard	Mass recovered for re-use and recycling (2007-2011)	Hardware, ink cartridges	EMEA, Americas	(9)
IBM	Mass collected for re-use and recycling as compared to mass sold same year (2011), percentage recycled, resold, re-used, waste to energy, landfilled	No information	Worldwide	(10)
Lenovo	Mass processed (2007-2010), Mass to Recycling, Waste to Energy, Incineration, Re-use, Disposal	No information	No information	(11)
LG Electronics	Mass collected and recycled (2007-2011)	Household appliance, IT, display	Worldwide	(12)
Motorola	Units recycled (2011)	Accessories, batteries, handsets, modems, other hardware	No information	(13)

Nokia	Number of countries covered by collection programs, Number of people reached through campaigns, Mass collected (2011), Comparison to mass collected previous year	Handsets, accessories	Worldwide	(14)
Oki Electric	Mass collected (2010), Material recycling and re-use rate (2010)	ATMs, printers, PCs, other	No information	(15)
Panasonic	Mass collected (2007-2011), Mass collected as compared to mass sold same year (2007-2011)	WEEE	Europe	(16)
	Mass collected (2011)	TV, PC, printer, notebook, other	Americas	(16)
	Mass collected, Units collected, Material recovery rate (2012)	PC, CRT, notebook, LCD, home appliances	Japan	(16)
Philips	Mass recycled (2005-2007)	Displays, other consumer electronics	Europe	(17)
Samsung	Mass recycled (2004-2010), Mass collected as compared to mass sold x years prior (based on an average life-span of 10 years for TVs, 7 years for computers, 2 years for mobile phones)	Houshold appliances, cooling equipment, displays, small appliances	Europe, Asia, North America	(18)
Sanyo	Mass recycled, Raw Materials recovered (2011)	TV, washer and dryer, cooling equipment, air conditioner	Japan	(19)
Sharp	Units collected (2011), Units processed and recycled (2006-2011), Mass processed and recycled (2011), Recycling rate as compared to legally required recycling rate (2005-2010), Raw materials recovered (2011), Mass processed and recycled as compared to mass sold 10 years ago	Air conditioners, monitors, washer and dryer, cooling equipment	Japan	(20)
	Mass recycled	No information	United States, Europe	(20)
Sony	Mass collected (2000-2010)	No information	Europe, North America, South Korea	(21)
	Mass collected (2000-2010), Mass collected as compared to mass sold x years prior (based on an average life-span of 10 yeras for TVs and 7 yeras for computers)	No information	Japan	(21)
Sony Mobile Communications	Units recycled (2011), Units recycled as compared to units sold same year (2011)	Phone	No information	(22)
Toshiba	Mass collected	No information	No information	(23)

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B Estimation of Trial Input Material Composition (Literature Data)

To estimate the type and amount of material that was fed to the process, literature data was collected and compared. The following tables show the concentration of different materials for the nine product categories contained in the trial feed. Based on the weight of category 1-9, the overall amount of ferrous, non-ferrous and other material contained in each product category was calculated.

It is difficult to find reliable data for some of the product categories (e.g. cordless phones, printers). In many cases, the data that was available did not show the level of detail that was required for this study, for example many datasets did not provide data on PM content. For some categories two or more datasets were available, which enabled the comparison of the values. As can be seen in for the product categories 1-5 and 8, the data obtained from the different literature references varies greatly. In fact, many data points vary over 100%, e.g. copper content of desktop PCs (category 3). For some values, however, the data shows only small variation, e.g. ferrous metal in PCs.

Because there is no reference point of comparison for some products, and because of the variation of data in the other product groups, it is not feasible to draw reliable conclusions on the overall material composition of the trial feed. The data is however helpful to answer some of the questions that might arise when looking at the total (actual) raw material yields from the trail (see figure 3.5). For example, over 50% of the ferrous material that was recovered in the trial, can be estimated to originate from the desktop PCs, in which an estimated 5,714 kg (average value) of ferrous material was contained. The same is true for the PM, which can be estimate to originate largely from the desktop PCs.

Trial Category 1: CRT Monitor														
Material	**Concentration per unit (18)**	**(7)**	**(9)**	**(11)**	**(17)**	**(19)**	**Unit**	**In Sample Batch (12080 kg) (18)**	**(7)**	**(9)**	**(11)**	**(17)**	**(19)**	**Unit**
Ferrous metals	14.7	9.0	8.1	10.4	3.0	9.0	%	1775.8	1091.9	981.1	1250.4	362.4	1087.2	kg
Steel	6.6		5.3	3.9			%	797.3		634.8	470.2			kg
Iron	8.1		2.9	6.5			%	978.5		346.3	780.2			kg
Non-ferrous metals														
Copper	7.8	6.1	4.9	8.5	4.0		%	942.2	735.7	596.1	1022.0	483.2		kg
Aluminum	0.4	0.3	2.1			0.5	%	48.3	40.0	248.1			60.4	kg
Gold		0.7	0.9				ppm		8.5	10.7				g
Silver		11.0	14.3				ppm		132.9	173.1				g
Palladium		0.3	0.3				ppm		3.6	4.0				g
Rest	0.5		0.4	14.3	13.0	13.5	%	60.4		51.8	1731.9	1570.4	1630.8	kg
Other														
Plastics	28.5	17.8	18.3	22.1	18.0	20.0	%	3442.8	2149.5	2207.1	2670.2	2174.4	2416.0	kg
Glass	48.1	64.1	57.6	44.3	62.0	46.0	%	5810.5	7745.2	6959.7	5355.9	7489.6	5556.8	kg
Other		2.6	8.6	0.4		11.0	%		317.7	1036.0	49.6		1328.8	kg
Total	**100**	**100**	**100**	**100**	**100**	**100**	**%**	**12080**	**12080**	**12080**	**12080**	**12080**	**12080**	**kg**

Trial Category 3: Desktop PCs														
Material	**Concentration per unit (18)**	**(10)**	**(4)**	**(12)**	**(6)**	**(20)**	**Unit**	**In Sample Batch (8564 kg) (18)**	**(10)**	**(4)**	**(12)**	**(6)**	**(20)**	**Unit**
Ferrous metals	63.9	66.0	69.2	68.7	64.9	67.6	%	5472.4	5654.9	5925.3	5883.0	5555.6	5793.1	kg
Steel	62.8	61.4	64.3	67.8	63.0		%	5378.2	5260.1	5505.2	5805.3	5395.4		kg
Iron	1.1	4.6	4.9	0.9	1.9		%	94.2	394.8	420.1	77.7	160.3		kg
Non-ferrous metals														
Copper	4.8	6.3	4.2	2.9	4.8	7.5	%	411.1	537.6	363.4	248.7	411.0	641.6	kg
Aluminum	5.0	3.1	5.7	3.7	14.3	4.9	%	428.2	269.6	483.9	312.9	1222.8	421.3	kg
Gold			26.7	0.0		40.3	ppm			228.7	0.0		344.7	g
Silver			174.8	13.7		156.5	ppm			1496.8	116.9		1340.6	g
Palladium			12.3	0.0			ppm			105.5	0.0			g
Rest	1.1	13.3	0.9	0.2	12.6	1.0	%	94.2	1138.2	73.3	21.1	1078.9	88.1	kg
Other														
Plastics	24.9	10.8	16.2	21.2	2.9	7.3	%	2132.4	923.1	1389.1	1815.8	250.0	622.4	kg
Glass	0.1			2.0			%	8.6			168.8			kg
Other	0.2	0.5	3.8	1.3	0.5	11.6	%	17.1	40.6	327.1	113.6	45.7	995.8	kg
Total	**100**	**100**	**100**	**100**	**100**	**100**	**%**	**8564**	**8564**	**8564**	**8564**	**8564**	**8564**	**kg**

Trial Category 2: LCD Monitor								
Material	**Concentration per unit**			**Unit**	**In Sample Batch (703 kg)**			**Unit**
	(1)	**(10)**	**(9)**		**(1)**	**(10)**	**(9)**	
Ferrous metals	39.5	49.5	37.1	%	277.9	347.8	261.1	kg
Steel	37.2	30.4	37.1	%	261.6	213.6	260.8	kg
Iron	2.3	19.1	0.0	%	16.3	134.2	0.3	kg
Non-ferrous metals								
Copper	2.3	3.1	6.1	%	16.3	21.8	42.9	kg
Aluminum		0.6	4.6	%		4.5	32.6	kg
Gold			39.4	ppm			27.7	g
Silver			102.3	ppm			71.9	g
Palladium			8.1	ppm			5.7	g
Rest	9.3	2.8	0.2	%	65.4	19.7	1.1	kg
Other								
Plastics	34.9	36.9	43.5	%	245.2	259.3	306.0	kg
Glass		5.5		%		38.4		kg
Other	14.0	1.6	8.4	%	98.1	11.5	59.2	kg
Total	**100**	**100**	**100**	**%**	**703**	**703**	**703**	**kg**

Trial Category 4: Laptops										
Material	**Concentration per Unit**				**Unit**	**In Sample Batch (222 kg)**				**Unit**
	(10)	**(16)**	**(1)**	**(3)**		**(10)**	**(16)**	**(1)**	**(3)**	
Ferrous metals	17.1	12.4	11.1	23.0	%	38.0	27.4	24.7	51.2	kg
Steel	17.1	11.6		23.0	%	38.0	25.8		51.2	kg
Iron		0.8			%		1.7			kg
Non-ferrous metals										
Copper	2.6	4.3	1.9	7.1	%	5.8	9.6	4.1	15.9	kg
Aluminum	1.3	16.4		13.5	%	2.9	36.4		30.1	kg
Gold		20.4		95.2	ppm		4.5		21.1	g
Silver		67.4		370.4	ppm		15.0		82.2	g
Palladium					ppm					g
Rest	33.8	1.7	29.6	0.4	%	75.0	3.7	65.8	1.0	kg
Other										
Plastics	29.8	44.3	14.8	29.7	%	66.2	98.3	32.9	65.9	kg
Glass	12.7	16.2			%	28.2	36.1			kg
Other	2.6	4.7	42.6	26.1	%	5.8	10.5	94.6	57.9	kg
Total	**100**	**100**	**100**	**100**	**%**	**222**	**222**	**222**	**222**	**kg**

Trial Category 5: Printing Devices						
Material	**Concentration per unit**		**Unit**	**In Sample Batch (6668 kg)**		**Unit**
	(14)	**(15)**		**(14)**	**(15)**	
Ferrous metals	35.5	18.6	%	2367.1	1240.9	kg
Steel		18.6	%		1240.9	kg
Iron			%			kg
Non-ferrous metals						
Copper	3.2	1.3	%	213.4	87.4	kg
Aluminum	0.2	4.4	%	13.3	294.2	kg
Gold			ppm			g
Silver			ppm			g
Palladium			ppm			g
Rest	7.4	13.6	%	493.4	903.9	kg
Other						
Plastics	45.8	58.3	%	3053.9	3884.9	kg
Glass			%			kg
Other	7.9	3.9	%	526.1	256.7	kg
Total	**100**	**100**	**%**	**6667**	**6668**	**kg**

Trial Category 6: IT Misc. (router, modem, etc.)				
Material	Concentration per unit (19)	Unit	In Sample Batch (69 kg) (19)	Unit
Ferrous metals	20.1	%	13.8	kg
Steel	20.1	%	13.8	kg
Iron		%		kg
Non-ferrous metals				
Copper		%		
Aluminum	1.3	%	0.9	kg
Gold		ppm		
Silver		ppm		
Palladium		ppm		
Rest	39.3	%	27.1	kg
Other				
Plastics	38.9	%	26.8	kg
Glass		%		kg
Other	0.5	%	0.3	kg
Total	**100**	**%**	**69**	**kg**

Trial Category 7: IT Accessoires (keyboard, mouse)								
Material	Concentration per unit (6) keyboard	(11) keyboard	(6) mouse	Unit	In Sample Batch (1555 kg) (6) keyboard	(11) keyboard	(6) mouse	Unit
Ferrous metals	7.3	9.2		%	102.7	128.0		kg
Steel	7.3			%				kg
Iron		9.2		%		128.0		kg
Non-ferrous metals								
Copper	4.3	5.4	16.3	%	60.2	76.2	25.4	kg
Aluminum				%				kg
Gold				ppm				kg
Silver				ppm				kg
Palladium				ppm				kg
Rest	1.8	32.7	5.3	%	24.5	457.2	8.2	kg
Other								
Plastics	86.6	52.7	54.7	%	1211.7	737.6	85.1	kg
Glass				%				kg
Other			23.7	%			36.8	kg
Total	**100**	**100**	**100**	**%**	**1399**	**1399**	**155**	**kg**

Trial Category 9: Cordless Phones				
Material	Concentration per unit (5)	Unit	In Sample Batch (87 kg) (5)	Unit
Ferrous metals	13.0	%	11.3	kg
Steel		%		kg
Iron		%		kg
Non-ferrous metals				
Copper	10.0	%	8.7	kg
Aluminum	2.0	%	1.7	kg
Gold	120.0	ppm	10.4	g
Silver	1350.0	ppm	117.5	g
Palladium	95.0	ppm	82.7	g
Rest	1.8	%	1.6	kg
Other				
Plastics	41.0	%	35.7	kg
Glass		%		kg
Other	32.0	%	27.8	kg
Total	**100**	**%**	**87**	**kg**

Trial Category 8: Cell Phone

Material	Concentration per unit (7)	(2)	(8)	(5)	(13)	Unit	In Sample Batch (10 kg) (7)	(2)	(8)	(5)	(13)	Unit
Ferrous metals	2.4	7.0	8.0	5.0	3.0	%	0.2	0.7	0.8	0.5	0.3	kg
Steel						%						kg
Iron						%						kg
Non-ferrous metals												
Copper	26.8	13.0	14.2	13.0	15.0	%	2.7	1.3	1.4	1.3	1.5	kg
Aluminum	2.3		2.9	1.0		%	0.2		0.3	0.1		kg
Gold	800.0	347.0	380.0	350.0		ppm	8.0	3.5	3.8	3.5		g
Silver	800.0	3630.0	2430.0	1340.0		ppm	8.0	36.3	24.3	13.4		g
Palladium	610.0	151.0	150.0	210.0		ppm	6.1	1.5	1.5	2.1		g
Rest		4.2	4.2	0.9	4.0	%		0.4	0.4	0.1	0.4	kg
Other												
Plastics	44.0	41.0	59.6	57.0	58.0	%	4.4	4.1	6.0	5.7	5.8	kg
Glass	5.5	34.0	10.6	2.0		%	0.6	3.4	1.1	0.2		kg
Other	18.4		0.2	21.0	20.0	%	1.8		0.0	2.1	2.0	kg
Total	**100**	**100**	**100**	**100**	**100**	**%**	**10**	**10**	**10**	**10**	**10**	**kg**

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C Estimation of Trial Input Material Composition (Empirical Data)

In addition to the analysis of literature data (see appendix B), the preparation of the pre-processing trial included a collaboration with researchers from KERP Competence Center in Vienna, Austria, who have deleoped a methodology and software tool to analyze the material composition of mixed WEEE. The methodology is a top-down approach in which the trial feed is categorized into the nine product categories. For each category, WEEE Analysis Service KERP has assessed empirical data through in-depth dismantling of multiple products of the same category and preparation of datasets that represent average product composition. Compared to the BOM of electronics that can be found in the literature, the material data assessed in these dismantling analyis is very explicit. For example, different types of plastics are identified, whereas most literatur references only show a general value for plastics. Missing components in the a mixed batch of WEEE can be taken into account (e.g. some cables and HDs were missing in the trial feed, see table 3.5) in the calculation.
The below table shows the estimated mass of several different materials in the trial feed that was handled for the empirical case in chapter 3. Compared with the mass of Ferrous material, Aluminum, Copper and PM that was detected in the trial, the data seems reasonable with the exeption of Aluminum, where the mass of Aluminum that was detected in four output streams (approx. 50% of the mass of all output streams) is almost equals the amount that was present in the trial feed. The value for Aluminum is likely to be underestimated.
The analysis shows that a rough estimation of the material composition of a mixed WEEE batch is feasible, if substantial amount of data is available on the products contained in the batch and the materials contained in electronics and electronics components.

Material Group	Material Subgroup	Mass in Trial Feed (g)
Ferrous TOTAL		**10,683,355**
Hazardous Component	Ammonium chloride	4
	Lead	15,481
	Silver oxide	587
	Indium tin oxide	70
	Lithium	1,622
	Magnetite	4,389
	Mercury	626
	Other hazardous	42,038
Hazardous TOTAL		**64,815**
Non-Ferrous	**Aluminum**	**1,175,561**
	Aluminum oxide	137,593
	Calcium oxide	44,972
	Chromium	6,885
	Gold	**416**
	Copper	**1,631,557**
	Magnesium oxide	6,484
	Manganese oxide	162,534
	Nickel	2,612
	Palladium	**117**
	Silver	**3,368**
	Tungsten	6
	Zinc	27,445
	Tin	38,881
Non-Ferrous TOTAL		**3,238,431**

D Scope of Environmental Data

The following table shows which datasets were selected from the ecoinvent 2.1 database. If available, global aggregated datasets (GLO) or RER (describing a process in Europe) datasets were selected over datasets for a country specific situation. For GLO datasets, ecoinvent allocates the country specific datasets according to the average global production shares from the years 2000 to 2004. If GLO or RER datasets are not available, a country specific dataset for the dominant producer is selected. If multiple GLO datasets are available for one material, material specific criteria (e.g. mining method) are considered.

Substance	Dataset Name (primary production)	Dataset ID	Location	Inventory boundary	Dataset Name (secondary production)	Dataset ID	Location	Inventory Boundary	Reference
Aluminum	Aluminium, primary, at plant	1054	RER	The dataset includes: **mining of bauxite, first mechanical grinding and processing of the ore, production of aluminum hydroxide, production of aluminum oxide, production of liquid aluminum, and finally production of cast aluminum ingot.** The dataset also includes mining infrastructure and land transformation due to mining, transport between different production sites, production infrastructure and the disposal of the wastes.	Aluminium, secondary, from old scrap, at plant Shredding, electrical and electronic scrap	1060 1094	RER GLO	The dataset captures the secondary aluminum production process: **sorting and preparing (e.g. cleaning, pressing) of post-consumer ('old') aluminum scrap, melting, alloying and casting of old scrap to secondary cast aluminum billets.** The dataset also includes transport of input materials to the plant, infrastructure of preparing, melting and casting, as well as emissions and disposal of wastes.	(1)
Copper	Copper, primary, at refinery	1084	GLO	The dataset captures the primary copper production process: **mining of copper ore, beneficiation, pre-treatment, the reduction and the refining of copper to cathode copper** (a mix of metallurgical processes is assumed for the latter step). The mining infrastructure, land transformation due to mining, the infrastructure of the reduction and refining process (furnace), as well as the disposal of overburden and tailings.	Copper, secondary, at refinery Shredding, electrical and electronic scrap	1092 1094	RER GLO	The dataset describes the production of secondary copper and includes: **treatment of copper scrap in a furnace, refining to copper cathodes.** The dataset already includes the dataset 'iron scrap, at plant', which is used as a proxy to cover transport and preparation of scrap. The infrastructure for leaching and pyrometallurgy, as well as disposal of wastes are also included.	(1)
Ferrous Metals	Steel, converter, low-alloyed, at plant	1150	RER	This dataset includes the primary steel production process: **mining of iron ore, sorting, beneficiation, reduction in blast furnace, processing in basic oxygen furnace (BOF)**. The mining infrastructure, land transformation due to mining, the infrastructure of the metallurgical processes, as well as transport activities from mine to plant (and transport of other inputs) are also included.	Steel, electric, un- and low-alloyed, at plant Shredding, electrical and electronic scrap	1153 1094	RER GLO	This dataset includes: **processing of scrap metal in an electric arc furnace (EAF), steel making process and casting**. The dataset also includes transport of the scrap and other inputs to the plant, disposal of wastes and emissions, as well as the infrastructure of the EAF process.	(1)
Gold	Gold, primary, at refinery	10120	GLO	This dataset combines multiple datasets for "gold, primary, at refinery" on a country level and includes: **mining of ore, ore processing (e.g. milling, oxidation, leaching, stripping), smelting and refining.** Mining, smelting and refining infrastructure, emissions and land use of the mining and production and some transport activities are also included.	Gold, secondary, at precious metals refinery Iron scrap, at plant Shredding, electrical and electronic scrap	8142 1101 1094	SE RER GLO	This dataset is part of the multi-output process 'precious metal refining, secondary copper' and captures the processing of e-scrap in the Boliden process. The dataset includes: **treatment of e-scrap in a Kaldo converter, treatment in converter aisle, anode slime treatment, production of secondary gold by Wohlwill eletrolysis.** The metallurgy infrastructure and emissions are also included. The dataset 'iron scrap, at plant' is used as a proxy to cover transportation and mechanical preparation of the scrap.	(1)

Silver	Silver, from combined gold-silver production, at refinery	10122	GLO	This dataset combines multiple datasets for "silver, from combined gold-silver production, at refinery" on a country level and includes: **mining of ore, ore processing, smelting and refining.** Mining, smelting and refining infrastructure, emissions and land use of the mining and production and some transport activities are also included..	Silver, secondary, at precious metals refinery Iron scrap, at plant Shredding, electrical and electronic scrap	8144 1101 1094	SE RER GLO	This dataset is part of the multi-output process 'precious metal refining, secondary copper' and captures the processing of e-scrap in the Boliden process. The dataset includes: **treatment of e-scarp in a Kaldo converter, treatment in converter aisle, anode slime treatment, production of secondary silver by Mübius eletrolysis.** The metallurgy infrastructure and emissions are also included. The dataset 'iron scrap, at plant' is used as a proxy to cover transportation and mechanical preparation of the scrap.	(1)
Palladium	Palladium, primary, at refinery	1129	RU	This dataset includes the production of primary palladium: **mining, beneficiation, metallurgy, separation of co-products (nickel and copper) and refining** as part of the multi-output process "platinum group metal production, primary". Mining and metallurgy infrastructure, disposal of overburden and tailings,emissions of most agents used in beneficiation and metallurgy, as well as some transport activities are also included. A dataset for production in Russia is selected, because a GLO dataset is not available and Russia was the major producer (44% of global production) in 2010.	Palladium, secondary, at refinery Shredding, electrical and electronic scrap	1130 10904	RER GLO	The dataset is part of the multi-output process "platinum group metal production, secondayr" and describes the recovery secondary palladium from EOL autocatalysts. The dataset includes: **beneficiation, metallurgical treatment in an arc-furnace, refining**. Production, application and emissions of the most important agents, plant infrastructure, and some transport activities are also included. There is no dataset available for the recovery of secondary palladium from e-scrap so this dataset was used as a proxy. It is estimated that the values in this dataset overestimate the resource use and impact of secondary palladium from e-scrap.	(1) (3)
					Shredding, electrical and electronic scrap	10904	GLO	This dataset includes: The **infrastructure for the mechanical treatment at a modern shredder facility (two shredders, two magnetic separation, and two eddy current steps), the energy consumption of all shredding and separation activities, as well as emissions to air**. Transport of the scrap from the collection point to the pre-processing facility are also included.	(2)
					Iron scrap, at plant	1101	RER	This dataset includes: **Transport of scrap to the palnt, pre-sorting of scrap and infrastructure of pre-sorting.**	(1)

References Appendix D

(1) Classen, M., Althaus, H.-J., Blaser, S., Scharnhorst, W., Tuchschmid, M., Jungbluth, N. and Faist Emmenegger, M. (2009). Life Cycle Inventories of Metals. Data v2.1. ecoinvent Centre (Swiss Centre for Life Cycle Inventories), St. Gallen, Switzerland.

(2) Hischier, R., Classen, M., Lehmann, M. and Scharnhost, W. (2007). Life Cycle Inventories of Electric and Electronic Equipment: Production, Use and Disposal. ecoinvent report No. 18. Part V: Disposal of Electric and Electronic Equipment (e-Waste). ecoinvent Centre (Swiss Centre for Life Cycle Inventories), St. Gallen, Switzerland.

(3) Loferski, P. J. (2011). Platinum Group Metals. United States Geological Service (USGS), Reston, Virginia, USA.

E Average Recovery Rates of a Copper Smelter

The following table shows average substance recovery rates of a copper smelter. The table is derived from p. 102 in Huisman, J. (2003). The QWERTY/EE concept. Quantifying Recyclability and Eco-Efficiency for End-of-Life Treatment of Consumer Electronic Products. Doctoral Thesis, Delft University of Technology, Delft, The Netherlands.

Element	Recovery Rate
Copper	95%
Silver	97%
Gold	98%
Palladium	98%
Nickel	90%
Lead	90%
Tin	90%
Cadmium	90%
Mercury	90%

F Actual and Potential AEB (Data)

The below tables show the data that underlies figures 3.13 to 3.19 in this study. The values are based on the empirically assessed and modeled (actual and potential) raw material yields of the empirical recycling case, and the environmental data shown in appendix D.

AEB of Actual Yields						
Material	**CED ren. (MJe)**	**CED non-ren. (MJe)**	**CED TOTAL (MJe)**	**CExD ren. (MJe)**	**CExD non-ren. (MJe)**	**CExD TOTAL (MJe)**
Steel	11,390.1	163,721.6	175,111.7	17,218.3	238,625.1	255,843.4
Aluminum	10,284.0	43,733.4	54,017.4	14,260.8	46,511.6	60,772.4
Copper	7,838.3	16,187.2	24,025.5	13,925.8	174,186.7	188,112.5
Gold	2,679.7	34,406.2	37,085.9	6,763.4	83,700.8	90,464.2
Silver	727.5	7,196.4	7,923.9	1,449.2	14,964.4	16,413.6
Palladium	155.3	3,648.6	3,803.9	768.4	4,007.1	4,775.6
TOTAL	**33,074.8**	**268,893.4**	**301,968.3**	**54,386.0**	**561,995.7**	**616,381.6**

AEB of Potential Yields						
Material	**CED ren. (MJe)**	**CED non-ren. (MJe)**	**CED TOTAL (MJe)**	**CExD ren. (MJe)**	**CExD non-ren. (MJe)**	**CExD TOTAL (MJe)**
Steel	11,635.7	167,251.6	178,887.4	17,589.5	243,770.1	261,359.7
Aluminum	24,278.4	103,246.1	127,524.6	33,667.0	109,804.8	143,471.8
Copper	14,746.7	30,454.1	45,200.7	26,199.6	327,709.4	353,909.0
Gold	4,628.3	59,425.2	64,053.5	11,681.5	144,565.0	156,246.5
Silver	1,439.4	14,238.3	15,677.7	2,867.3	29,607.6	32,474.9
Palladium	352.0	8,271.7	8,623.8	1,742.2	9,084.5	10,826.7
TOTAL	**57,080.5**	**382,887.1**	**439,967.6**	**93,747.1**	**864,541.5**	**958,288.6**

AEB of Actual Yields					
Material	**GWP (kg CO2e)**	**EF (m2a)**	**AP (CML 2001) (kg SO2e)**	**NP (CML 2001) (kg PO4e)**	**HTP (CML 2001) (kg 1.4-DCBe)**
Steel	13,471.5	32,461.3	51.5	13.3	81,036.5
Aluminum	3,495.2	8,927.4	15.3	1.4	18,013.2
Copper	1,007.0	3,691.1	348.7	407.6	483,636.6
Gold	2,169.8	6,811.9	23.2	129.7	47,607.2
Silver	512.0	1,467.6	8.0	15.0	5,355.5
Palladium	210.1	677.5	199.8	0.4	401.5
TOTAL	**20,865.7**	**54,036.8**	**646.6**	**567.5**	**636,050.5**

AEB of Potential Yields					
Material	**GWP (kg CO2e)**	**EF (m2a)**	**AP (CML 2001) (kg SO2e)**	**NP (CML 2001) (kg PO4e)**	**HTP (CML 2001) (kg 1.4-DCBe)**
Steel	13,762.0	33,161.2	52.6	13.6	82,783.8
Aluminum	8,251.6	21,075.8	36.0	3.3	42,525.7
Copper	1,894.6	6,944.3	656.0	766.9	909,898.8
Gold	3,747.6	11,765.3	40.1	224.1	82,225.3
Silver	1,013.0	2,903.7	15.9	29.8	10,596.2
Palladium	476.3	1,536.0	453.1	0.8	910.1
TOTAL	**29,145.1**	**77,386.4**	**1,253.7**	**1,038.4**	**1,128,939.9**

Curriculum Vitae

Irina Oswald
Geb. am 02.02.1984
In Landshut

Juni 2010 – März 2012	Wissenschaftliche Mitarbeiterin am Lehrstuhl für Ressourcenstrategie, Institut für Physik, Universität Augsburg
Juli 2009 – Mai 2010	Research Assistant, oekom research AG
Nov. 2008	Diplom Physische Geographie
März 2006 – Nov. 2008	Studium der Physischen Geographie, Institut für Angewandte Informatik, Universität Augsburg
Sept. 2005 – Feb. 2006	Studium der Physischen Geographie, Université Joseph Fourier Grenoble
Okt. 2003 – Aug. 2005	Studium der Geographie, Georg-August Universität Göttingen (Vordiplom)
Juni 2003	Allgemeine Hochschulreife
Sept. 1994 – Juni 2003	Gymnasium Seligenthal Landshut